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A comparison of the load carrying characteristics of hydrostatic thrust bearing using monatomic, diatomic, and triatomic gases

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A COMPARISON OF THE LOAD CARRYING CHARACTERISTICS
OF A HYDROSTATIC THRUST BEARING USING MONATOMIC,
DIATOMIC, AND TRIATOMIC GASES

BY

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A

THESIS

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ABSTRACT

The purpose of this investigation is to compare the load carrying characteristics of gases with different ratios of specific heat. The design, construction, and operation of an apparatus for testing and comparing the load carrying characteristics of gases are described. Several monatomic, diatomic, and triatomic gases were tested and the results evaluated and compared. The data are tabulated and displayed in a series of curves.

It was found that the monatomic gases exhibit a greater clearance for a given load and a greater total load carrying capacity than the diatomic gases which in turn have a greater clearance and total load carrying capacity than the triatomic gases and that an increase in molecular weight decreases clearance and total load carrying capacity.

ACKNOWLEDGEMENT

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Thanks are also due Mr. Gaynol Greenwood for his assistance in building the test apparatus and in conducting the experiments.

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I. INTRODUCTION

Since man invented the wheel, lubrication of bearings has been important. Through the centuries many lubricants have been used which were largely of animal, vegetable, or marine origin. The use of mineral oil as the principle lubricant is relatively recent and dates back approximately one hundred years to the discovery of oil at Titusville, Pa., in 1859. Although the idea of gas lubricated bearings were suggested as long ago as 1854 by Hirn (1), only recently have they aroused a great amount of interest. The reason for this interest is their advantages over other types of bearings for the following applications:

1. High temperature lubrication where ordinary liquid or grease lubricants fail.
2. Bearings operating in radio-active atmospheres where conventional lubrication may break down.
3. Applications sensitive to contamination where fouling from lubricating oil becomes serious.
4. Low-friction devices.
5. High-Speed devices.
6. Applications where positional accuracies within microinches are required.

An extensive survey of literature conducted by Mr. B. D. Shiwalker (2) revealed that many people are working in the field of gas lubricated bearings. Gas lubricated bearings have

(1) (2) All references are in the bibliography.

been used for a variety of purposes both in the laboratory and in industry, but there is a definite lack of published information relating to their systematic design and the effect of various parameters on their performance. One of the parameters thought to affect performance is the ratio of specific heats which according to the classical kinetic theory of gases has values of 5/3, 7/5, and 9/7 respectively for monatomic, diatomic, and triatomic gases (3). As pointed out by Mr. Shiwalker, and confirmed by the author, there are no published data showing the effect of variation in the specific heat ratio on the performance of a hydrostatic thrust bearing.

This thesis reports the work involved in (a) preparing a suitable bearing and test device for comparing the load carrying characteristics of monatomic, diatomic, and triatomic gases (b) calibrating, testing, and taking data, and (c) evaluating the resulting data to determine the effect of the specific heat ratio on the load carrying characteristics of the bearing.

II. SURVEY OF LITERATURE

Gas lubricated bearings can be one of two types, either hydrodynamic or hydrostatic.

The hydrodynamic bearing generates its own pressure within the clearance space between the two elements of the bearing by virtue of the fluid and the relative motion of the bearing elements.

In the hydrostatic bearing the load is supported by the static gas pressure in the clearance space between the two elements of the bearing. There is always an outward leakage of the gas which must be replaced by gas pumped from an external source through feed holes in the bearing wall. To economize on gas, flow restrictors in series with gas admission holes or recesses are often used. They can take the form of capillaries or orifices. On this basis, they may be divided into orifice compensated bearings or capillary compensated bearings. When the orifice is formed at the junction of hole (d) and gap (h) (Figure 1), the bearing is called the inherent orifice type. Hydrostatic bearings can be either journal or thrust bearings. Thrust bearings can be of almost any configuration however flat, spherical, or conical bearings are the most common.

A major part of the experimental work on hydrostatic thrust bearings has been conducted by Laub (4), Richardson (5), Wunsch (6), Pigott and Macks (7), Corey (8) and McNeilly (9). Laub has conducted experiments on circular step thrust bearings (Figure 2).

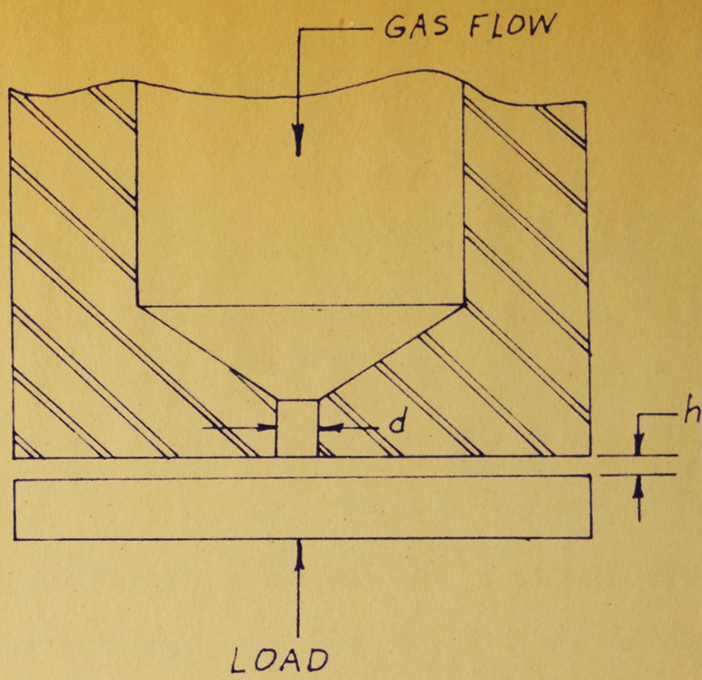


Figure 1

Single - Hole Circular Inherent Orfice Compensated Thrust Bearing

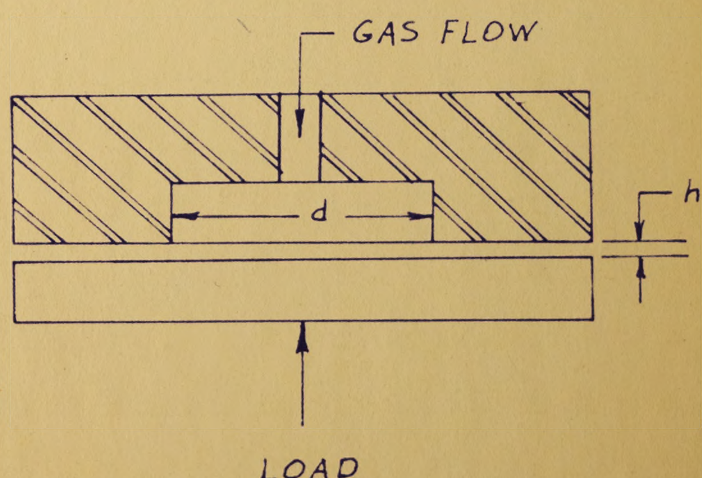


Figure 2

Circular Step Thrust Bearing

Richardson has reported his work on rectangular pad thrust bearings. Wunsch has experimented with thrust bearings with various set back locations of the orifice.

Pigott and Macks have experimented with capillary compensated bearings. Corey has written of his experiments with spherical thrust bearings (Figure 3) and McNeilly has investigated the inherent orifice type thrust bearing (Figure 1).

The bearing tested in this investigation was a hydrostatic inherent orifice type thrust bearing as shown in Figure 1. Its characteristics with air as the working fluid have been investigated by Mr. V. H. McNeilly. Its design was chosen for this test sequence because of its simplicity and the availability of comparative data concerning its operating characteristics.

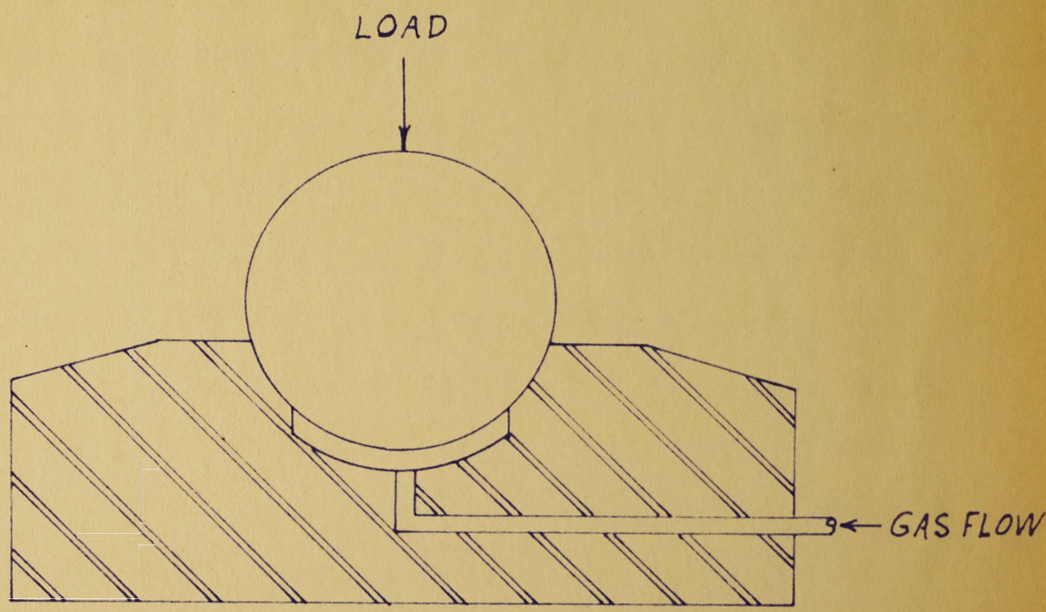


Figure 3

Spherical Thrust Bearing

III. DISCUSSION

A. Description of the Experimental Test Apparatus

The test apparatus shown in Figures 4, 5, and 6 was designed and built by the author for this experiment. Its principal components are a pressure regulator, gas filter, control valve, pressure chamber, pressure gauge, dial indicator, thrust bearing plates, thrust plate guide bearing, load beam, and weight platform.

The pressure regulator used was a standard oxygen pressure regulator which indicated both bottle and line pressure. (Figure 4). The line pressure could be varied from zero to four hundred psig. Several adapters were obtained and a connector was made so that the oxygen regulator could be connected to any commercial gas cylinder.

The filter was made from two inch diameter thin walled aluminum tubing with flanges at each end. The tube was sealed at the flange with an "O" ring. The filter was filled with Drierite, a commercial product for removing moisture from a gas, sandwiched between several pads of steel wool. Operation of the filter indicated the need for several inches of steel wool to prevent dust from the Drierite entering the pressure chamber. A thermometer was used to read the temperature of the gas entering the pressure chamber and a gate valve was used to control the pressure of the gas in the pressure chamber.

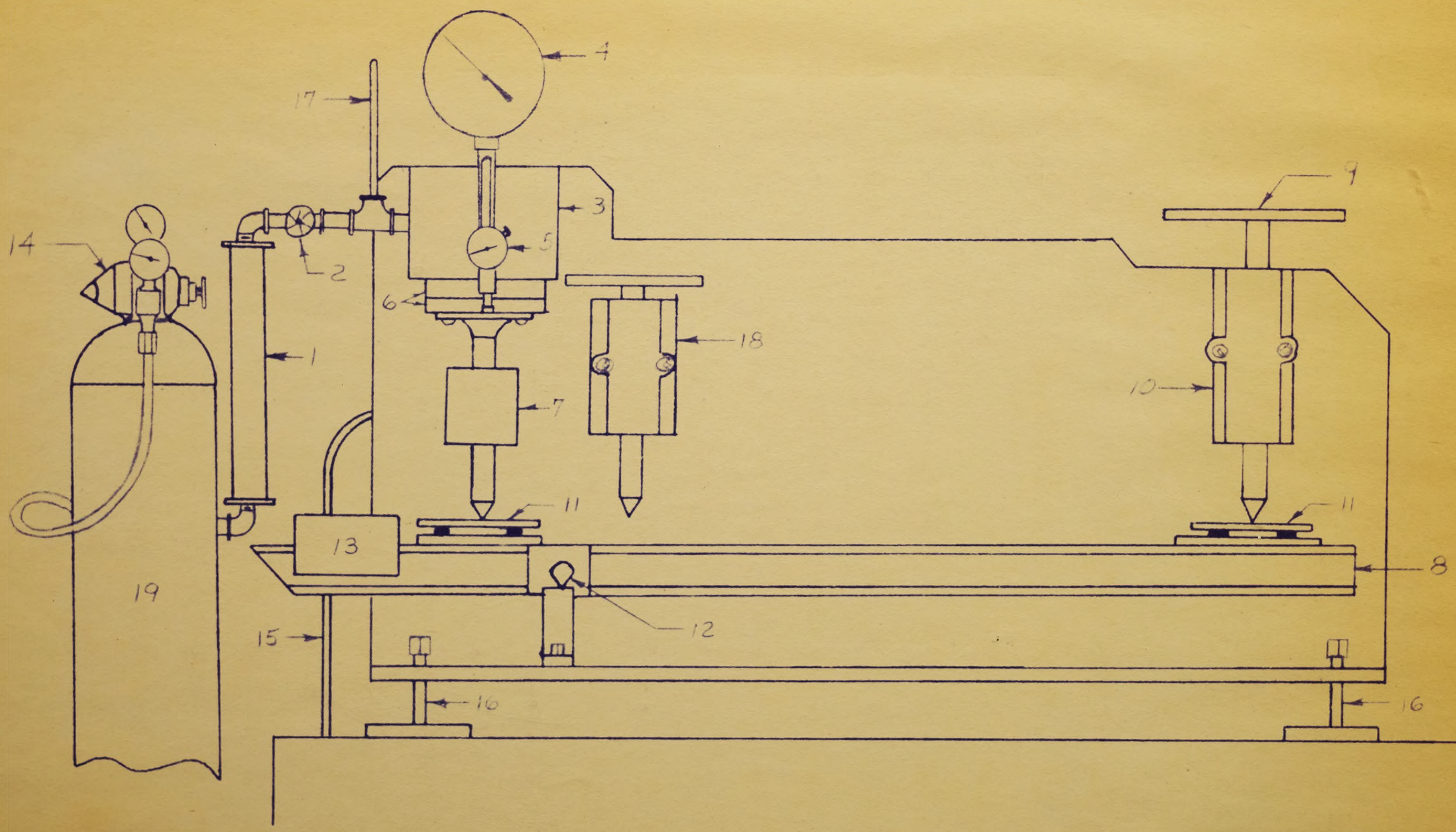


Figure 4

Schematic of the Test Apparatus Used
To Obtain Data for Test One and Two

Key to Figure 4:

No.	1	Gas Filter
	2	Pressure Control Valve
	3	Pressure Chamber
	4	Pressure Gauge
	5	Dial Indicator
	6	Thrust Bearing Plates
	7	Thrust Plate Guide Bearing
	8	Load Beam
	9	Weight Platform
	10	Weight Platform Bearing
	11	Linear Ball Bearing
	12	Load Beam Pivot
	13	Counter Balance Weight
	14	Pressure Regulator
	15	Air Line to Thrust Plate Bearing
	16	Leveling Jacks
	17	Thermometer
	18	Second Load Platform
	19	Gas Bottle

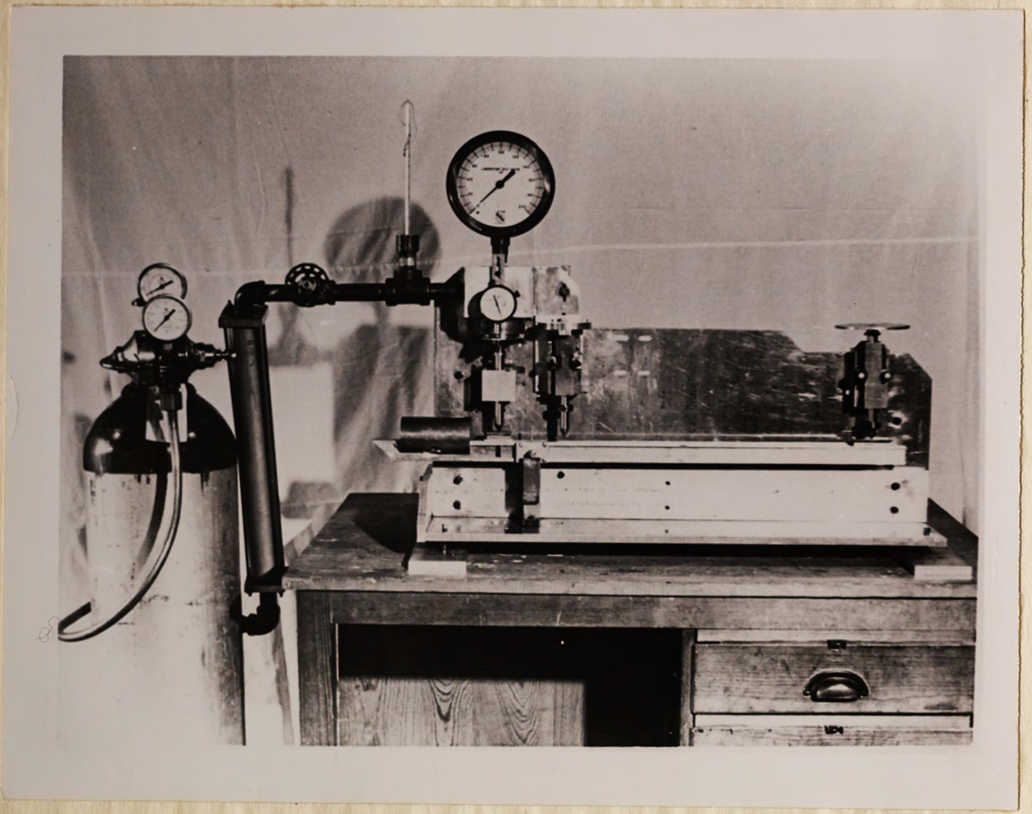


Figure 5

Front View of the Test Apparatus Used to
Obtain Data for Test One and Two

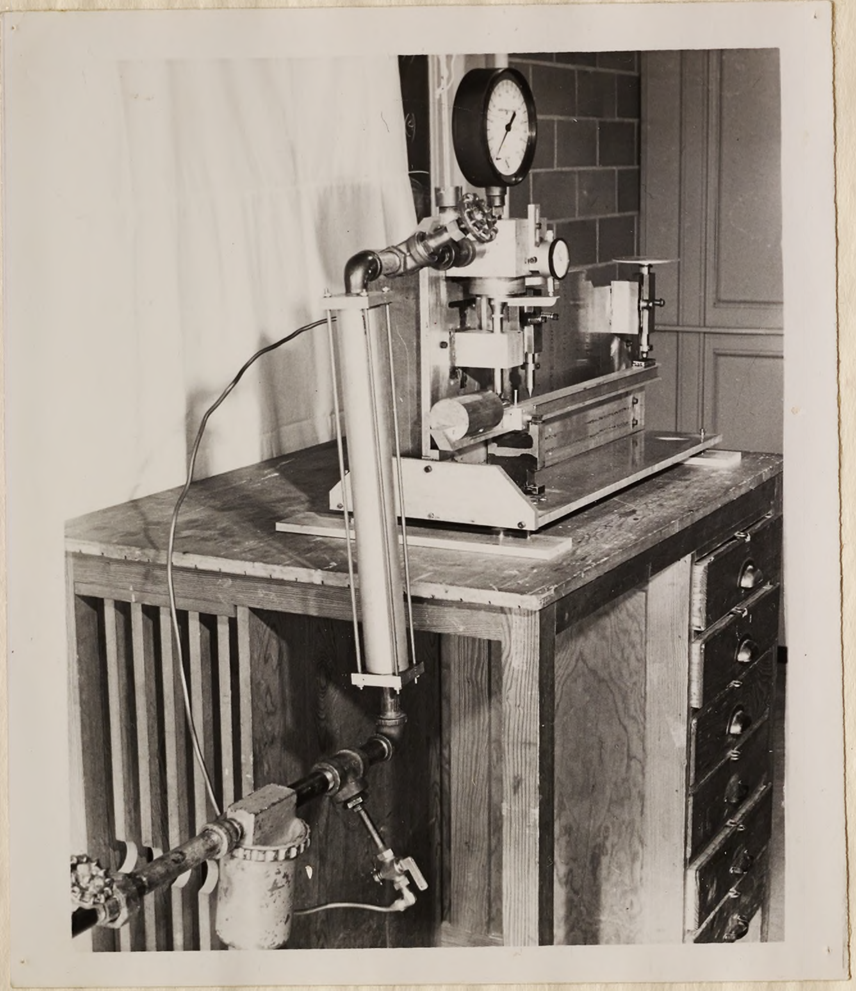


Figure 6

Side View of the Test Apparatus Used to Obtain Data for Test One and Two

The pressure chamber was made from a four by four by three inch block of aluminum. It was bored out as shown in Figure 7. An "O" ring groove was cut and an "O" ring installed in it to form a gas tight seal between the pressure chamber and the thrust bearing plate. A pressure gauge was mounted on top of the chamber to read the chamber pressure. Before using this gauge it was calibrated on an Ashcroft Dead Weight Tester.

The thrust bearing plates were made as shown in Figure 8. They were machined in the Mechanical Engineering machine shop. The plates were made from cold rolled steel by turning down the outside diameters to three inches. Both faces of each bearing were faced on a lathe and the surfaces ground flat on a surface grinder. The .125 inch diameter orifice was drilled in the top plate. The plates were hardened by immersion in a cyanide bath until the depth of the cyanide case was approximately .010 inch thick. This thickness was determined by observing the grain structure of a piece of cold drawn test wire. The plates were quenched in oil and tempered at approximately four hundred degrees fahrenheit for one hour. The hardened plates were then reground on the surface grinder and lapped. Carborundum lapping compound in cutting oil was used first, then jewelers rouge in oil. Each bearing was lapped against a cast iron plate in which grooves were cut to form a checkered pattern. The plates were lapped until nearly flat as indicated by an optical flat (Figure 8).

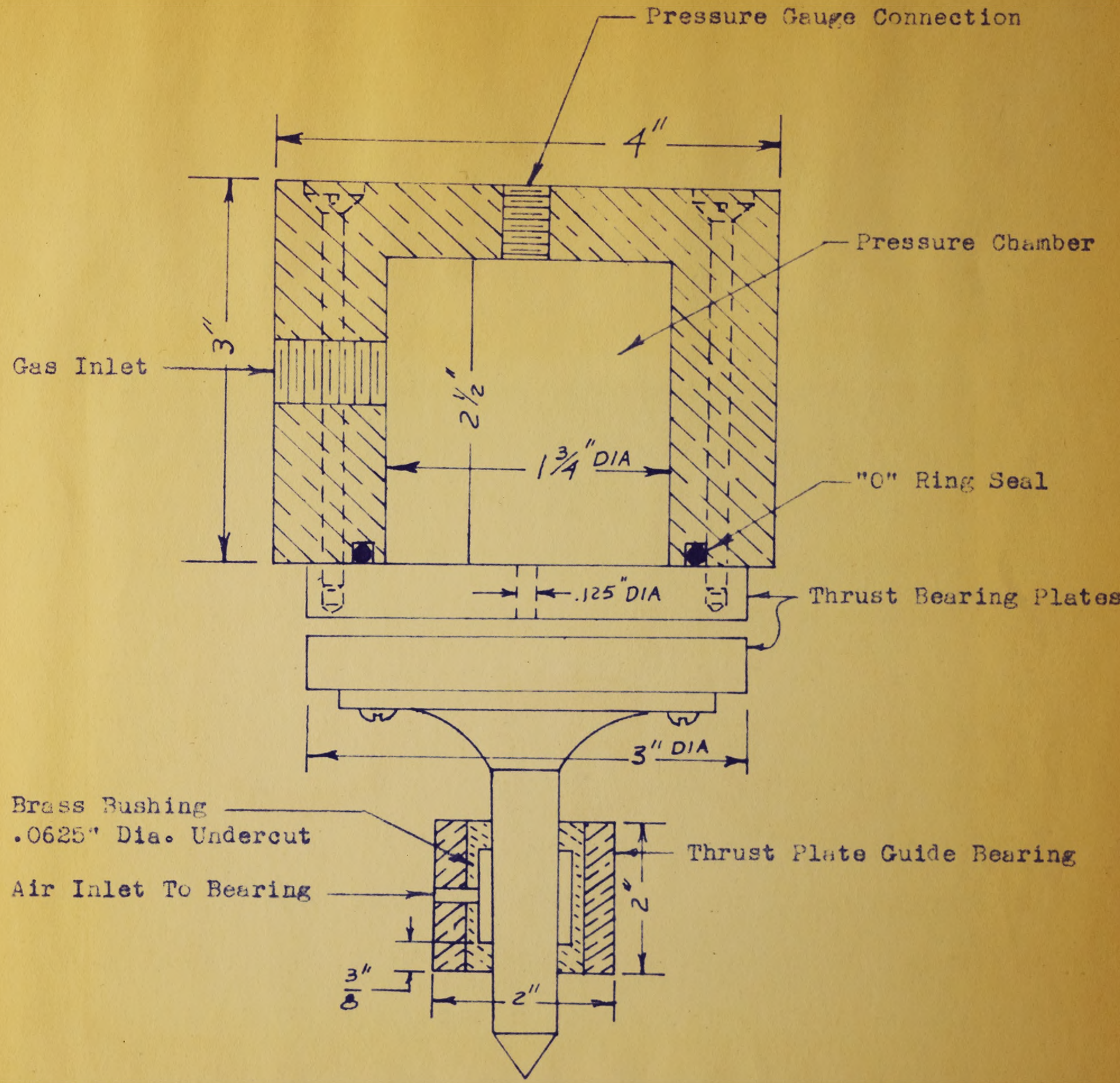


Figure 7

Schematic of the Pressure Chamber, Thrust Bearing Plates, and Thrust Plate Guide Bearing

Figure 8

Thrust Bearing Plates

A dial indicator graduated in ten thousandths of an inch increments and with two hundred thousandths of an inch travel was used. It was located so that it read clearance between the thrust bearing plates directly.

The thrust plate guide bearing was made from aluminum with a bronze insert. The insert was undercut .0625 inch in diameter in the center of the bearing so that there was .375 inch bearing surface at each end of the bearing (Figure 7). This was done to reduce bearing friction. The bearing was drilled, bored, and then honed so that a smooth, accurate, bearing surface was formed. The shaft was made from an internal combustion engine valve stem since this provided a surface which had been hardened and ground for accuracy. Air at approximately seventy-five psig pressure was fed into the bearing cavity at the middle and was allowed to flow around and out each end of the bearing. This produced a practically frictionless bearing.

The load beam consisted of an aluminum "I" section which was balanced on a knife edge. It was set up so that there was a multiplying factor of ten to one between the weight platform and the thrust bearing (Figure 4). A counter balance weight was used to balance the beam under no load operation.

The weight platform bearing was constructed as shown in Figure 9 and used as shown in Figure 4. Linear ball bearings were used as shown in Figure 4 to allow longitudinal motion between the shafts and the load beam. Paper spacers were used to retain the balls in the bearings. Ball bearings were used to allow as near frictionless motion of the weight platform as possible.

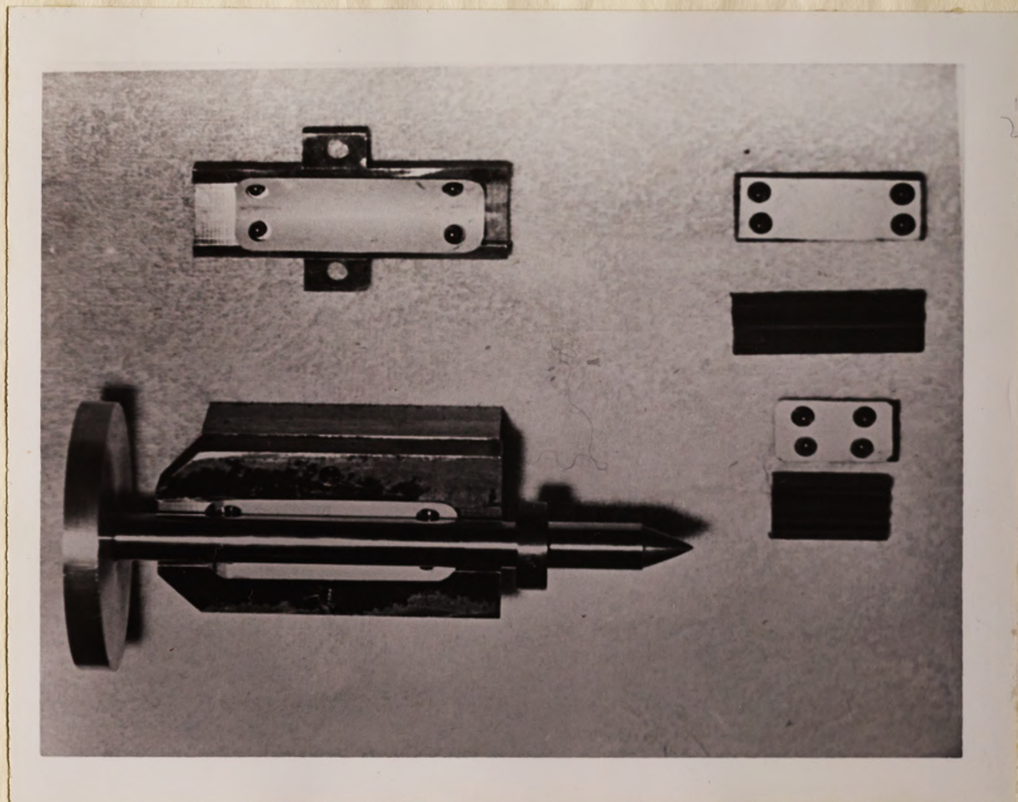


Figure 9

Weight Platform Bearing and Linear Ball Bearings

The frame was made from one half inch aluminum plate braced to provide required rigidity. It was supported on four jack screws so that it could be easily adjusted and leveled.

Air from the power plant was found to contain a large amount of moisture. Therefore, a water trap was installed between the air line and the air filter-dryer. This trap removed a major portion of the moisture before the air reached the drying agent (Figure 6).

Throughout the construction of the test apparatus each component was tested to see that it was satisfactory for the job intended. Many modifications were required to make each component work satisfactorily. The initial tests of the apparatus were made with air because of its availability. These tests showed the need for additional bracing of the unit and the elimination of as much friction in the bearings as possible which was done by constructing the bearings just described.

Data similar to that shown in Graph 1 were taken and plotted prior to actual testing. They were found comparable in shape and magnitude to that reported by McNeilly for a similar bearing. Data taken during any day were found to be consistent but it varied from day to day. It was felt that this change was due to the wide temperature and moisture variations experienced with the air rather than mechanical difficulties. Therefore, gases other than air were tested. Since the only area of interest in bearing design is the positive force region to the left in Graph 1, this was the only region tested using gases other than air. The data shown in Tables I thru XII, for Test One and Test Two, and the positive load data shown in Table XIII were taken using the equipment arrangement just discussed.

Graph 1 shows the load versus clearance between the plates over a wide range of clearances for air at seventy-five psig. It is noted that a negative force is required to separate the plates in the portion of the curve to the right of the point where force equals zero. This portion of the curve was obtained using the same apparatus, with a shorter load beam and a different weight platform (Figures 10 and 11). This arrangement allowed negative loads to be placed on the thrust bearing by adding weights to the weight pan under the table top. The load beam was adjusted for a one to one multiplication factor and the beam was balanced by placing weights on the load pan until, when the beam was level, no change in the dial indicator was noted when the frame of the test apparatus was vibrated slightly to help overcome inertia and friction. Since large clearances were encountered in this portion of the curve, gauge blocks were placed under the dial indicator stem to extend its travel. Appropriate gauge blocks were placed on the load beam under the thrust plate guide bearing shaft so that the load beam remained relatively level during the test. The weight contributed by the gauge blocks was counterbalanced by other gauge blocks of equal weight. The data shown in Table XIII were obtained using this equipment arrangement.

In order to improve the accuracy and reproducibility of the data it was decided to modify the apparatus as shown in Figure 12. The purpose of the modification was to remove as much structural deflection as possible and to eliminate the clearance between the thrust plate guide bearing and its shaft. The thrust plate guide bearing was replaced by a linear ball bearing similar to the type used for the weight platform. These bearings operate without clearance. Bracing was added to the structure and a fifth jack screw, located near the fulcrum of the load beam, was installed to prevent deflection of the structure. The dial indicator was relocated so that it read directly from the thrust bearing plate thus eliminating any deflection of the extension arm from the thrust bearing. The new location also reduced the amount of moment placed on the lower thrust plate by the dial indicator return spring.

The data shown in Tables XVII thru XX for the third test were taken using this improved arrangement.

B. Experimental Procedure and Data Taking

Three critical adjustments had to be made on the test apparatus before testing. The load beam had to be adjusted so that it gave exactly a ten to one multiplying factor. The thrust bearing plates had to be parallel, and the beam had to be balanced.

The beam was adjusted by clamping a scribe to the load beam directly under the load platform. The beam was adjusted until the dial indicator read exactly one tenth the thickness of a gauge block placed under the scribe.

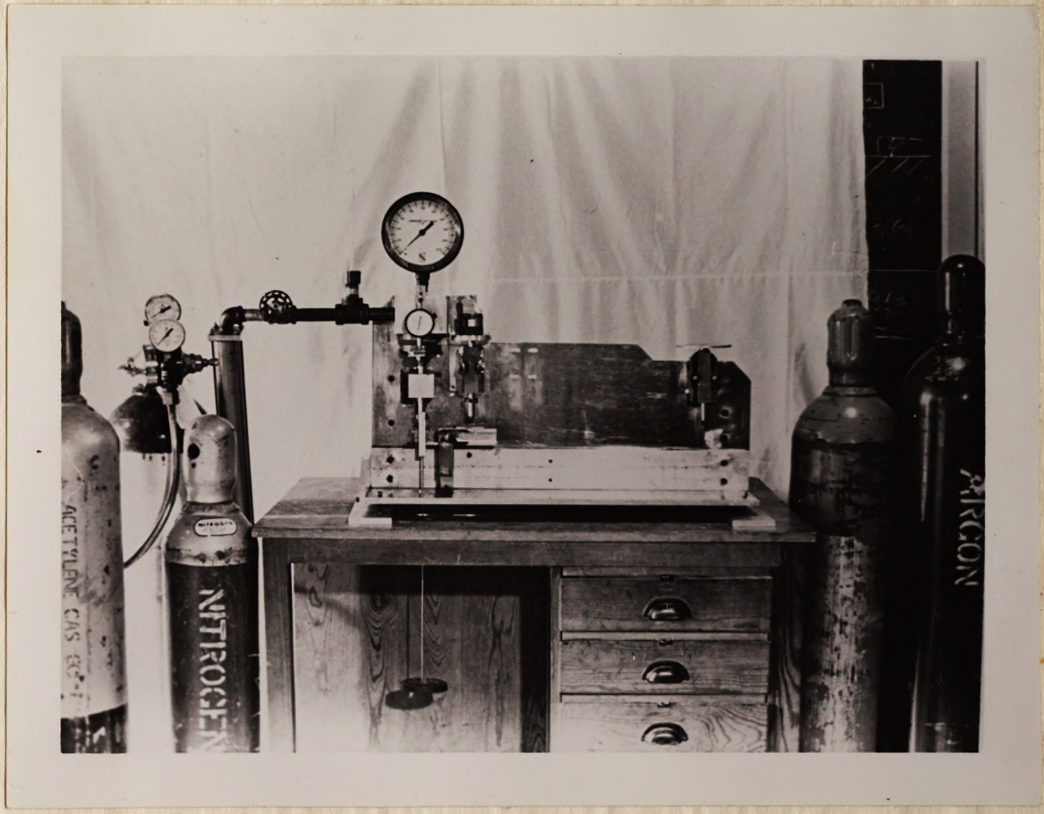


Figure 10

Test Apparatus Used to Obtain
Data Below the Positive Load Axis

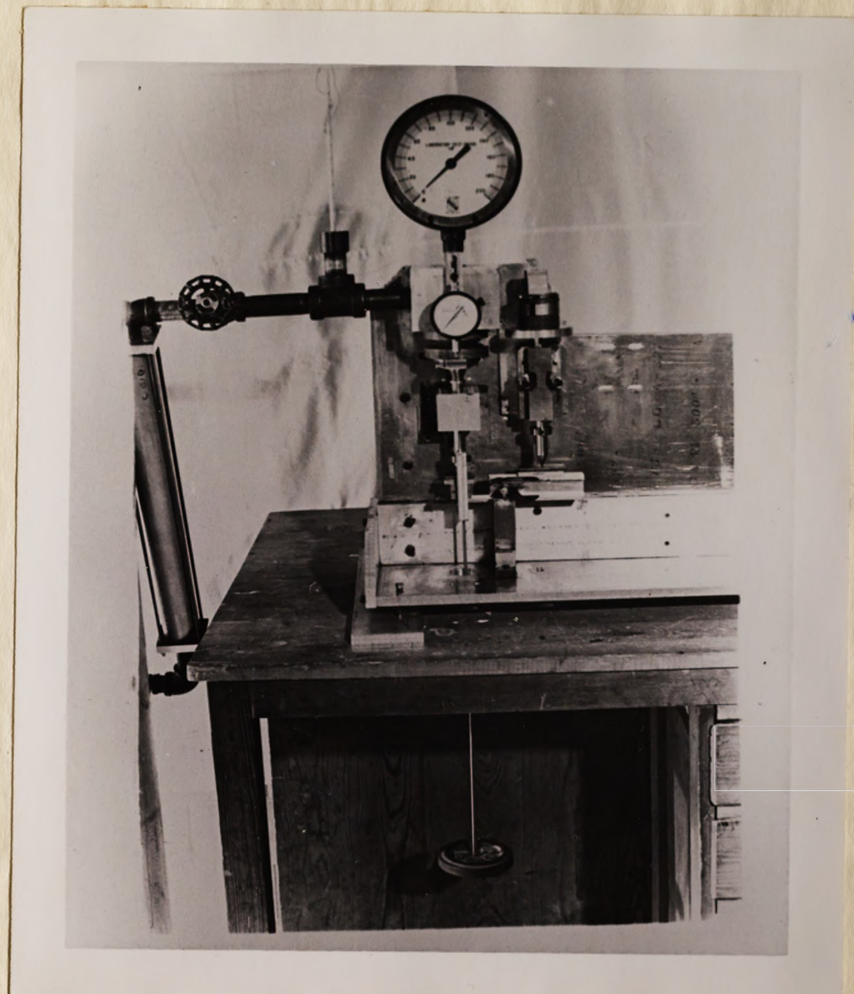


Figure 11

Close-up View of the Test Apparatus for Obtaining Data Below the Positive Load Axis

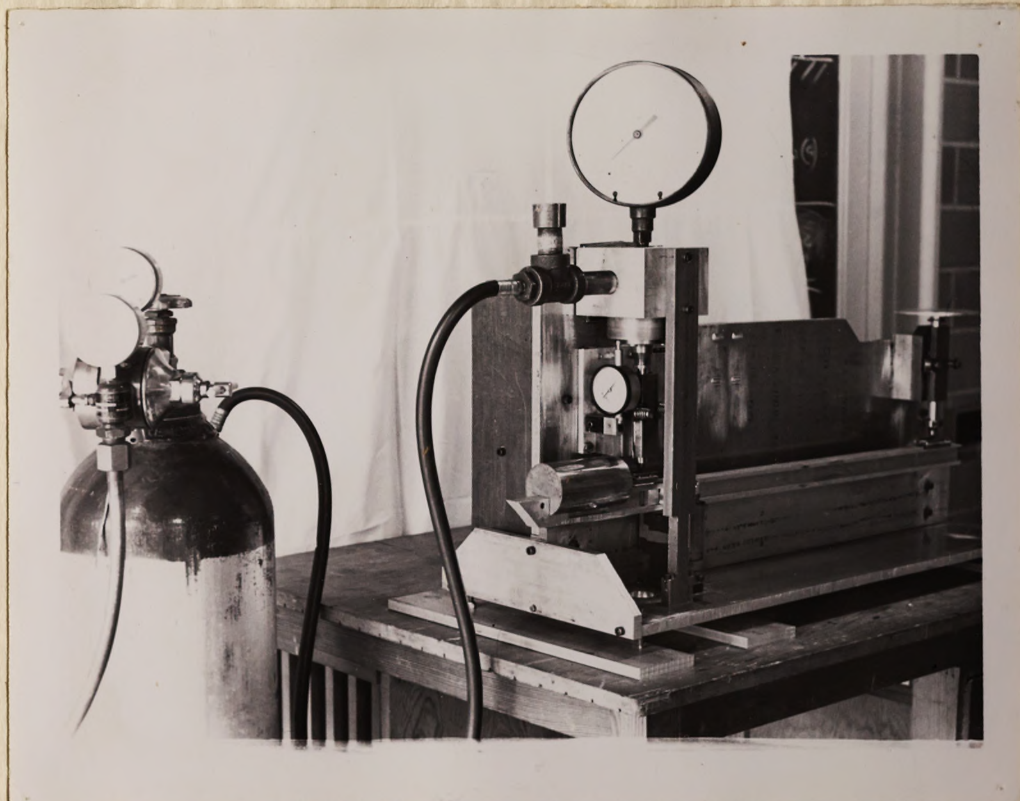


Figure 12

Test Apparatus Used to Obtain
Data for Test Three

Parallelism between the two bearing plates was obtained by shimming and adjusting the pressure chamber until the two plates were aligned. Parallelism was checked by testing the "pull" on four pieces of cigarette paper placed at ninety degree increments around the periphery of the bearing plates. Air was admitted to the thrust plate guide bearing and a small weight was placed on the weight pan forcing the thrust bearing plates together. The pressure chamber body which holds the upper thrust bearing plate was then adjusted until the force required to move each piece of paper was the same. A further check was made by removing the load from the thrust bearing and checking to see whether the molecular cohesive force would support the weight of the lower thrust plate and shaft. This was a good indication that the plates were clean, flat and parallel. In addition, it was found that by placing a small load on the bearings and then shining a light between them, very small misalignments could be detected and corrected. Further minute corrections could be made by adding additional load to the weight pan and observing the direction of deflection on the dial indicator. When the bearings were in perfect alignment the dial indicator showed no deflection with increasing load.

Balancing the load beam was another critical adjustment. The beam was balanced at a clearance between the plates of three thousandths of an inch. The balanced beam would not move either direction when the structure of the test device was gently vibrated.

After operating the test apparatus for several days it was noted that the data were consistent from one run to the next even though the relative position of the curves changed from day to day. It was felt that this variation was due to the change in moisture content, and the temperature of the air and not due to variations in the operation of the experimental apparatus. At this point tests using gases other than air were considered. The gases used had to be safe, nontoxic, non-corrosive, and readily available. The only gases readily available which met these requirements were argon and helium for monatomic gases, oxygen, nitrogen and air for diatomic gases, and carbon dioxide for a triatomic gas. These gases were tested in the following manner and the data recorded as Test One.

The drying agent in the filter was changed, the plates were checked for alignment, and the dial indicator was zeroed. Air was tested first. The air was turned on and adjusted with the control valve until the pressure in the pressure chamber was seventy-five psig at no load. The clearance between the bearings was read from the dial indicator and was recorded to five decimal places. The last decimal place was estimated. The load was increased in ten pound increments by placing one pound weights on the weight pan. The pressure was adjusted to seventy-five psig after each weight was added by adjusting the pressure control valve. The clearance between the plates was read and recorded. The process of adding one pound weights, readjusting pressure, and recording the clearance was repeated until the gap was completely closed. A one pound weight was then removed from the weight pan, the bearing gap was reopened by pulling down on the lower thrust bearing, and a one-half pound weight was added to the weight pan. If the bearing carried the load the reading was recorded and one-tenth pound weights were added and the deflection after adding each was recorded until the gap closed. If the one-half pound weight closed the gap it was removed, the gap reopened, and one-tenth pound weights added until the gap was closed. After the first run with a given gas at a given pressure the maximum load capacity could be predicted so that the trial and error selection of weights near the maximum load point could be avoided. The gas temperature was recorded after each run. Typical results of such a test procedure are shown in Table I.

Since the only area of interest in bearing design is the positive force region to the left in Graph 1, this was the only region tested.

After the air test the drying agent was changed in the filter and three runs using argon gas at seventy-five psig were made. This test was followed by three runs using nitrogen and three runs using oxygen each at seventy-five psig (Tables II, III, and IV).

As a check to see that the apparatus was still in calibration, a test run using argon at seventy-five psig was made and found to be in close agreement with data previously taken, (Run Four Table II). Three runs using carbon dioxide were made at seventy-five psig followed by three runs using helium (Tables V and VI). Another calibration run with argon was made indicating close agreement with previous data (Run Five Table II). As a final check two runs using air at seventy-five psig were made which proved to be in close agreement with the initial air data taken (Runs Four and Five Table I).

The test was continued in the following manner. Three runs using air at fifty psig and three runs using air at twenty-five psig were made. The drying agent was changed and the gases were tested in the following order at fifty and twenty-five psig: argon, nitrogen, oxygen, carbon dioxide, and helium. For data see Tables I thru VI. It was found during the testing that if the pressure regulator on the gas bottle was set close to the desired pressure, the pressure in the pressure chamber could easily be adjusted by the pressure control valve. This procedure was used during all tests.

A second set of data recorded as Test Two were taken with the test apparatus one week later. The test apparatus was unchanged from the previous test and the operating conditions were the same except for the temperatures of the room and the gases. Three runs using each gas were made at pressures of seventy-five, fifty, and twenty-five psig in the same manner as the previous test. Argon, nitrogen, oxygen, carbon dioxide, helium, and air were tested in that order and the data recorded as Test Two (Tables VII thru XII).

Air was tested to determine its load carrying characteristics over a wide range of deflections. It was tested at seventy-five psig only. The data are tabulated in Table XIII, and a plot of the data are shown in Graph 1. The test apparatus and procedures previously described were used to obtain the data for the positive load section of the curve. Figures 10 and 11 show the test apparatus arrangement used to obtain the data below the zero load axis. The short load beam was balanced by placing weights on the upper weight pan. After the beam was balanced, air pressure was maintained in the pressure chamber at seventy-five psig and weights were added to the weight pan under the table. Readings were taken and recorded at each load until the bearing would not support any additional load. Weights were then removed from the lower weight pan in one pound increments and the bearing was pulled apart to clearances greater than those observed at the point of maximum negative load. By trial and error, a neutral clearance was found where the bearing would not move when released. This point was then recorded.

The data taken in the previously described tests were then plotted and analyzed.

A comparison of Test One and Test Two is shown on Graph 5. It can be seen that the shape of the curves are practically identical but that the curves for test two are shifted to the left in the direction of less clearance. This shift is of the same magnitude for each gas for the same load. This indicates that the shape of the curves and the relative position of the various gases are correct and remain unchanged in comparative position between Tests One and Two. It was felt that the shift of the curves was of greater magnitude than would be expected by temperature alone. Further investigation revealed that at a given gas pressure and bearing load, the clearance between the plates changed in proportion to the magnitude and direction of a load applied to the pressure chamber. In order to eliminate this variation due to structural deflection and to further establish the validity of the test data, it was decided to modify and retest the apparatus with the gases which remained from the previous tests.

The purpose of the modification was to remove as much structural deflection as possible and to eliminate the clearance between the thrust plate guide bearing and the shaft. The modifications have been previously described and the modified test apparatus is shown in Figure 12. The only gases which remained in sufficient quantity to test were carbon dioxide, oxygen, and argon. These were tested at seventy-five psig in the same manner as the previous tests and recorded as Test Three. In addition, oxygen was tested on three consecutive days at different temperatures to determine, if possible, the effect of temperature change on the shape and location of the curves. For data see Tables XVII thru XX.

As a final statement of clarification, Test One was conducted using the basic equipment shown in Figures 4, 5, and 6. Test Two was made one week later using the same equipment and gases as Test One. Test Three was performed on the apparatus shown in Figure 12 which had been modified to make the structure more rigid.

TABLE I
AIR DATA TEST ONE
(Room Temperature 78° F)

Pressure 75 psig

LOAD POUNDS	CLEARANCE IN INCHES RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	AVERAGE
0	.00668	.00682	.00684	.00656	.00688	.00676
10	.00450	.00451	.00450	.00432	.00444	.00445
20	.00356	.00366	.00369	.00335	.00354	.00356
30	.00304	.00310	.00312	.00280	.00295	.00300
40	.00263	.00275	.00270	.00250	.00257	.00263
50	.00241	.00250	.00244	.00229	.00234	.00240
60	.00221	.00231	.00227	.00210	.00214	.00221
70	.00203	.00211	.00209	.00193	.00200	.00203
80	.00184	.00190	.00184	.00174	.00179	.00182
85	.00176	.00174	.00172	.00160	.00164	.00169
86	.00170	.00170	.00167	.00157	.00160	.00165
87	.00156	.00157	.00151	.00143	.00154	.00152
88	-	-	-	-	-	-
GAS TEMP °F	81	83	84	84	84	83

Pressure 50 psig

LOAD POUNDS	CLEARANCE IN INCHES RUN 1	RUN 2	RUN 3	AVERAGE
0	.00807	.00800	.00786	.00798
10	.00453	.00450	.00446	.00450
20	.00352	.00350	.00350	.00351
30	.00297	.00295	.00294	.00295
40	.00254	.00265	.00254	.00258
50	.00227	.00238	.00226	.00230
55	.00214	.00213	.00204	.00210
56	.00199	.00200	.00291	.00197
57	-	-	-	-
GAS TEMP °F	83	85	85	84

Pressure 25 psig

LOAD POUNDS	CLEARANCE IN INCHES RUN 1	RUN 2	RUN 3	AVERAGE
0	.00817	.00822	.00839	.00826
5	.00507	.00476	.00484	.00489
10	.00386	.00383	.00378	.00382
15	.00330	.00327	.00322	.00326
20	.00297	.00295	.00296	.00296
25	.00248	.00249	.00244	.00247
26	.00224	.00227	.00226	.00226
27	-	-	-	-
GAS TEMP °F	85	87	86	86

TABLE II
ARGON DATA TEST ONE
(Room Temperature 78° F)

Pressure 75 psig

LOAD	CLEARANCE IN INCHES					
POUNDS	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	AVERAGE
0	.00776	.00761	.00749	.00751	.00743	.00756
10	.00482	.00478	.00478	.00471	.00468	.00475
20	.00382	.00385	.00395	.00373	.00390	.00385
30	.00324	.00325	.00329	.00312	.00328	.00324
40	.00277	.00282	.00279	.00272	.00283	.00279
50	.00253	.00254	.00255	.00248	.00254	.00253
60	.00237	.00238	.00237	.00229	.00239	.00236
70	.00215	.00215	.00216	.00209	.00219	.00215
80	.00192	.00195	.00195	.00190	.00197	.00194
85	.00178	.00181	.00183	.00175	.00185	.00180
86	.00175	.00177	.00178	.00171	.00181	.00176
87	.00174	.00169	.00171	.00165	.00175	.00171
88	.00165	.00167	.00160	.00163	.00160	.00163
89	-	-	-	-	-	-
GAS TEMP °F	81	81	80	79	80	80

Pressure 50 psig

LOAD	CLEARANCE IN INCHES			
POUNDS	RUN 1	RUN 2	RUN 3	AVERAGE
0	.00740	.00774	.00773	.00762
10	.00450	.00441	.00440	.00444
20	.00350	.00348	.00344	.00347
30	.00297	.00295	.00290	.00294
40	.00258	.00257	.00252	.00256
50	.00230	.00226	.00222	.00226
55	.00207	.00205	.00208	.00207
56	.00196	.00199	.00197	.00197
57	.00168	.00170	.00175	.00171
58	-	-	-	-
GAS TEMP °F	82	81	81	81

Pressure 25 psig

LOAD	CLEARANCE IN INCHES			
POUNDS	RUN 1	RUN 2	RUN 3	AVERAGE
0	.00810	.00800	.00813	.00808
5	.00470	.00475	.00486	.00477
10	.00388	.00381	.00383	.00384
15	.00330	.00327	.00334	.00330
20	.00296	.00288	.00293	.00292
25	.00254	.00250	.00253	.00252
26	.00233	.00228	.00226	.00229
27	-	-	-	-
GAS TEMP °F	81	81	81	81

TABLE III
NITROGEN DATA TEST ONE
(Room Temperature 78° F.)

Pressure 75 psig

LOAD POUNDS	CLEARANCE IN INCHES RUN 1	RUN 2	RUN 3	AVERAGE
0	.00711	.00711	.00720	.00714
10	.00450	.00457	.00458	.00455
20	.00360	.00368	.00366	.00365
30	.00301	.00311	.00311	.00308
40	.00264	.00268	.00266	.00266
50	.00240	.00243	.00246	.00243
60	.00222	.00225	.00226	.00224
70	.00202	.00206	.00207	.00205
80	.00182	.00186	.00186	.00185
85	.00165	.00171	.00171	.00169
86	.00160	.00167	.00168	.00165
87	-	.00172	.00154	.00153
88	-	-	-	-
GAS TEMP °F	80	80	80	80

Pressure 50 psig

LOAD POUNDS	CLEARANCE IN INCHES RUN 1	RUN 2	RUN 3	AVERAGE
0	.00754	.00753	.00774	.00760
10	.00426	.00429	.00434	.00430
20	.00338	.00341	.00351	.00343
30	.00285	.00288	.00297	.00290
40	.00248	.00251	.00251	.00250
50	.00221	.00223	.00222	.00222
55	.00207	.00197	.00197	.00200
56	.00191	.00189	.00169	.00183
57	-	-	-	-
GAS TEMP °F	81	81	81	81

Pressure 25 psig

LOAD POUNDS	CLEARANCE IN INCHES RUN 1	RUN 2	RUN 3	AVERAGE
0	.00850	.00845	.00858	.00851
5	.00476	.00473	.00480	.00476
10	.00377	.00376	.00376	.00376
15	.00326	.00323	.00324	.00324
20	.00285	.00298	.00285	.00289
25	.00242	.00253	.00245	.00247
26	.00224	.00237	.00228	.00230
27	-	-	-	-
GAS TEMP °F	80	81	80	80

TABLE IV
OXYGEN DATA   TEST ONE
(Room Temperature 78° F.)

Pressure 75 psig

LOAD POUNDS	CLEARANCE IN INCHES RUN 1	RUN 2	RUN 3	AVERAGE
0	.00721	.00701	.00738	.00720
10	.00480	.00469	.00485	.00478
20	.00378	.00377	.00384	.00380
30	.00324	.00323	.00326	.00324
40	.00274	.00272	.00279	.00275
50	.00249	.00246	.00247	.00247
60	.00231	.00230	.00231	.00231
70	.00206	.00204	.00210	.00207
80	.00188	.00189	.00189	.00189
85	.00171	.00174	.00173	.00173
86	.00168	.00169	.00169	.00169
87	.00155	.00154	.00155	.00155
88	-	-	-	-
GAS TEMP °F	80	81	80	80

Pressure 50 psig

LOAD POUNDS	CLEARANCE IN INCHES RUN 1	RUN 2	RUN 3	AVERAGE
0	.00691	.00760	.00772	.00741
10	.00428	.00429	.00435	.00431
20	.00332	.00345	.00347	.00341
30	.00286	.00289	.00289	.00288
40	.00242	.00247	.00248	.00246
50	.00218	.00216	.00219	.00218
55	.00201	.00199	.00202	.00201
56	.00179	.00180	.00183	.00181
57	.00170	.00169	.00170	.00170
58	-	-	-	-
GAS TEMP °F	80	80	81	80

Pressure 25 psig

LOAD POUNDS	CLEARANCE IN INCHES RUN 1	RUN 2	RUN 3	AVERAGE
0	.00659	.00710	.00713	.00694
5	.00459	.00481	.00479	.00473
10	.00365	.00377	.00372	.00371
15	.00316	.00322	.00323	.00320
20	.00278	.00280	.00280	.00379
25	.00240	.00239	.00241	.00240
26	.00216	.00216	.00218	.00217
27	-	-	-	-
GAS TEMP °F	80	80	80	80

TABLE V
CARBON DIOXIDE DATA TEST ONE
(Room Temperature 78° F)

Pressure 75 psig

LOAD	CLEARANCE IN INCHES			
POUNDS	RUN 1	RUN 2	RUN 3	AVERAGE
0	.00645	.00653	.00649	.00649
10	.00395	.00404	.00400	.00400
20	.00305	.00311	.00306	.00307
30	.00252	.00259	.00256	.00256
40	.00222	.00226	.00226	.00225
50	.00198	.00203	.00202	.00201
60	.00184	.00188	.00187	.00186
70	.00163	.00167	.00165	.00165
80	.00142	.00149	.00145	.00145
81	.00139	.00143	.00141	.00141
82	-	-	-	-
GAS TEMP °F	80	80	79	80

Pressure 50 psig

LOAD	CLEARANCE IN INCHES			
POUNDS	RUN 1	RUN 2	RUN 3	AVERAGE
0	.00625	.00633	.00625	.00628
10	.00348	.00357	.00352	.00352
20	.00271	.00281	.00278	.00277
30	.00228	.00238	.00231	.00232
40	.00198	.00202	.00199	.00200
50	.00165	.00168	.00166	.00166
51	.00163	.00164	.00161	.00163
52	-	-	-	-
GAS TEMP °F	82	81	82	82

Pressure 25 psig

LOAD	CLEARANCE IN INCHES			
POUNDS	RUN 1	RUN 2	RUN 3	AVERAGE
0	.00632	.00664	.00657	.00651
5	.00387	.00386	.00387	.00387
10	.00306	.00299	.00298	.00301
15	.00258	.00251	.00248	.00252
20	.00230	.00232	.00234	.00232
25	.00180	.00181	.00186	.00182
26	-	-	-	-
GAS TEMP °F	80	80	80	80

TABLE VI
HELIUM DATA TEST ONE
(Room Temperature 78° F.)

Pressure 75 psig

LOAD	CLEARANCE IN INCHES			
POUNDS	RUN 1	RUN 2	RUN 3	AVERAGE
0	.01100	.01129	.01132	.01120
10	.00748	.00760	.00754	.00754
20	.00592	.00615	.00618	.00608
30	.00507	.00526	.00526	.00520
40	.00447	.00458	.00460	.00455
50	.00400	.00417	.00416	.00411
60	.00371	.00386	.00386	.00381
70	.00343	.00356	.00354	.00351
80	.00320	.00334	.00332	.00329
90	.00296	.00308	.00306	.00303
100	.00262	.00272	.00270	.00268
101	.00234	.00263	.00265	.00254
102	-	.00258	.00257	.00257
103	-	.00228	.00239	.00234
104	-	-	-	-
GAS TEMP °F	80	80	80	80

Pressure 50 psig

LOAD	CLEARANCE IN INCHES			
POUNDS	RUN 1	RUN 2	RUN 3	AVERAGE
0	.01213	.01200	.01172	.01195
10	.00742	.00720	.00716	.00726
20	.00578	.00560	.00556	.00565
30	.00493	.00482	.00487	.00487
40	.00435	.00438	.00436	.00436
50	.00395	.00394	.00393	.00394
60	.00350	.00350	.00350	.00350
65	.00310	.00306	.00304	.00307
66	.00280	.00254	.00264	.00266
67	-	-	-	-
GAS TEMP °F	79	79	79	79

Pressure 25 psig

LOAD	CLEARANCE IN INCHES			
POUNDS	RUN 1	RUN 2	RUN 3	AVERAGE
0	.01316	.01320	.01291	.01309
5	.00801	.00787	.00788	.00792
10	.00623	.00625	.00632	.00626
15	.00524	.00528	.00535	.00529
20	.00479	.00476	.00479	.00478
25	.00426	.00430	.00429	.00428
30	.00347	.00357	.00352	.00352
31	-	-	-	-
GAS TEMP °F	79	79	79	79

TABLE VII
AIR DATA TEST TWO
(Room Temperature 66° F)

Pressure 75 psig

LOAD POUNDS	CLEARANCE IN INCHES RUN 1	RUN 2	RUN 3	AVERAGE
0	.00646	.00631	.00639	.00638
10	.00404	.00396	.00407	.00402
20	.00311	.00302	.00317	.00310
30	.00265	.00247	.00263	.00258
40	.00226	.00215	.00224	.00222
50	.00202	.00193	.00199	.00197
60	.00183	.00172	.00187	.00181
70	.00167	.00158	.00173	.00166
80	.00155	.00142	.00155	.00151
85	.00142	.00138	.00143	.00141
86	.00135	.00130	.00136	.00134
87	.00126	.00125	.00127	.00126
88	-	-	-	-
GAS TEMP °F	73	72	74	73

Pressure 50 psig

LOAD POUNDS	CLEARANCE IN INCHES RUN 1	RUN 2	RUN 3	AVERAGE
0	.00689	.00710	.00729	.00709
10	.00365	.00377	.00378	.00373
20	.00276	.00285	.00393	.00285
30	.00227	.00236	.00240	.00234
40	.00196	.00198	.00205	.00200
50	.00167	.00174	.00176	.00172
55	.00154	.00151	.00160	.00155
56	.00147	.00145	.00148	.00147
57	.00134	.00133	.00137	.00135
58	-	-	-	-
GAS TEMP °F	73	73	74	73

Pressure 25 psig

LOAD POUNDS	CLEARANCE IN INCHES RUN 1	RUN 2	RUN 3	AVERAGE
0	.00785	.00775	.00787	.00782
5	.00443	.00435	.00438	.00439
10	.00341	.00331	.00340	.00337
15	.00238	.00280	.00287	.00283
20	.00245	.00239	.00240	.00244
25	.00200	.00199	.00204	.00202
26	.00187	.00185	.00186	.00186
27	.00167	.00167	.00169	.00168
GAS TEMP °F	74	74	75	74

TABLE VIII
ARGON DATA TEST TWO
(Room Temperature 66° F)

Pressure 75 psig

LOAD POUNDS	CLEARANCE IN INCHES			
	RUN 1	RUN 2	RUN 3	AVERAGE
0	.00679	.00633	.00663	.00658
10	.00429	.00421	.00416	.00422
20	.00332	.00322	.00322	.00325
30	.00272	.00261	.00266	.00266
40	.00236	.00221	.00230	.00229
50	.00209	.00195	.00205	.00203
60	.00191	.00178	.00186	.00185
70	.00174	.00161	.00171	.00168
80	.00156	.00147	.00157	.00153
90	.00125	.00125	.00126	.00125
91	-	-	-	-
GAS TEMP °F	62	63	63	63

Pressure 50 psig

LOAD POUNDS	CLEARANCE IN INCHES			
	RUN 1	RUN 2	RUN 3	AVERAGE
0	.00717	.00667	.00691	.00698
10	.00375	.00368	.00372	.00371
20	.00281	.00213	.00286	.00283
30	.00232	.00228	.00235	.00231
40	.00199	.00199	.00200	.00199
50	.00168	.00172	.00171	.00170
55	.00157	.00155	.00156	.00156
56	.00146	.00152	.00152	.00150
57	.00138	.00143	.00142	.00141
58	-	-	-	-
GAS TEMP °F	64	63	64	64

Pressure 25 psig

LOAD POUNDS	CLEARANCE IN INCHES			
	RUN 1	RUN 2	RUN 3	AVERAGE
0	.00693	.00692	.00715	.00700
5	.00418	.00425	.00427	.00423
10	.00312	.00319	.00322	.00317
15	.00264	.00269	.00268	.00267
20	.00229	.00230	.00230	.00230
25	.00194	.00192	.00192	.00193
26	.00178	.00175	.00177	.00176
27	.00164	.00168	.00160	.00164
28	-	-	-	-
GAS TEMP °F	63	64	65	64

TABLE IX
NITROGEN DATA TEST TWO
(Room Temperature 66° F.)

Pressure 75 psig

LOAD POUNDS	CLEARANCE IN INCHES RUN 1	RUN 2	RUN 3	AVERAGE
0	.00637	.00626	.00646	.00636
10	.00365	.00365	.00410	.00380
20	.00273	.00289	.00325	.00295
30	.00229	.00238	.00267	.00244
40	.00204	.00217	.00233	.00218
50	.00183	.00195	.00208	.00195
60	.00170	.00180	.00194	.00181
70	.00155	.00163	.00176	.00164
80	.00142	.00155	.00165	.00154
90	.00118	.00127	.00106	.00117
91	-	-	-	-
GAS TEMP °F	67	67	68	67

Pressure 50 psig

LOAD POUNDS	CLEARANCE IN INCHES RUN 1	RUN 2	RUN 3	AVERAGE
0	.00684	.00740	.00719	.00702
10	.00365	.00368	.00367	.00367
20	.00281	.00289	.00289	.00286
30	.00232	.00236	.00242	.00236
40	.00202	.00205	.00208	.00205
50	.00171	.00173	.00178	.00174
55	.00163	.00158	.00158	.00159
56	.00155	.00156	.00154	.00155
57	.00143	.00145	.00146	.00145
58	-	-	-	-
GAS TEMP °F	68	68	68	68

Pressure 25 psig

LOAD POUNDS	CLEARANCE IN INCHES RUN 1	RUN 2	RUN 3	AVERAGE
0	.00806	.00848	.00793	.00815
5	.00430	.00430	.00431	.00430
10	.00330	.00329	.00336	.00331
15	.00278	.00273	.00271	.00274
20	.00241	.00240	.00242	.00241
25	.00204	.00203	.00203	.00203
26	.00186	.00185	.00189	.00187
27	-	-	-	-
GAS TEMP °F	68	68	68	68

TABLE X
OXYGEN DATA TEST TWO
(Room Temperature 66° F.)

Pressure 75 psig

LOAD POUNDS	CLEARANCE IN INCHES RUN 1	RUN 2	RUN 3	AVERAGE
0	.00658	.00636	.00625	.00639
10	.00411	.00405	.00396	.00404
20	.00320	.00320	.00314	.00318
30	.00263	.00264	.00264	.00264
40	.00225	.00223	.00223	.00223
50	.00197	.00199	.00197	.00197
60	.00180	.00181	.00183	.00181
70	.00163	.00164	.00166	.00164
80	.00151	.00153	.00155	.00153
90	.00121	.00122	.00120	.00121
91	-	-	-	-
GAS TEMP °F	70	70	71	70

Pressure 50 psig

LOAD POUNDS	CLEARANCE IN INCHES RUN 1	RUN 2	RUN 3	AVERAGE
0	.00773	.00659	.00642	.00691
10	.00364	.00370	.00385	.00373
20	.00279	.00286	.00289	.00284
30	.00230	.00237	.00237	.00234
40	.00194	.00198	.00198	.00197
50	.00175	.00173	.00169	.00172
55	.00160	.00162	.00158	.00160
56	.00149	.00151	.00154	.00151
57	.00138	.00142	.00144	.00141
58	-	-	-	-
GAS TEMP °F	70	70	70	70

Pressure 25 psig

LOAD POUNDS	CLEARANCE IN INCHES RUN 1	RUN 2	RUN 3	AVERAGE
0	.00666	.00661	.00627	.00651
5	.00424	.00428	.00426	.00426
10	.00334	.00319	.00324	.00325
15	.00271	.00268	.00278	.00272
20	.00236	.00232	.00227	.00231
25	.00197	.00197	.00192	.00195
26	.00180	.00176	.00171	.00175
27	.00166	.00162	.00163	.00163
28	-	-	-	-
GAS TEMP °F	71	71	70	71

TABLE XI
CARBON DIOXIDE DATA TEST TWO
(Room Temperature 66° F.)

Pressure 75 psig

LOAD POUNDS	CLEARANCE IN INCHES RUN 1	RUN 2	RUN 3	AVERAGE
0	.00525	.00535	.00536	.00532
10	.00313	.00303	.00316	.00311
20	.00236	.00233	.00240	.00236
30	.00194	.00188	.00199	.00194
40	.00164	.00165	.00168	.00166
50	.00147	.00147	.00150	.00148
60	.00136	.00135	.00139	.00137
70	.00120	.00120	.00123	.00121
80	.00104	.00098	.00103	.00102
80	-	-	-	-
GAS TEMP °F	69	67	64	67

Pressure 50 psig

LOAD POUNDS	CLEARANCE IN INCHES RUN 1	RUN 2	RUN 3	AVERAGE
0	.00529	.00547	.00537	.00538
10	.00273	.00285	.00277	.00278
20	.00213	.00210	.00213	.00212
30	.00167	.00166	.00170	.00168
40	.00148	.00145	.00147	.00147
50	.00120	.00117	.00119	.00119
51	.00111	.00117	.00115	.00114
52	.00109	.00106	.00105	.00107
53	-	-	-	-
GAS TEMP °F	63	62	62	62

Pressure 25 psig

LOAD POUNDS	CLEARANCE IN INCHES RUN 1	RUN 2	RUN 3	AVERAGE
0	.00479	.00511	.00506	.00499
5	.00337	.00338	.00341	.00339
10	.00246	.00239	.00243	.00243
15	.00200	.00196	.00201	.00199
20	.00181	.00172	.00178	.00177
25	.00142	.00132	.00140	.00138
26	-	-	-	-
GAS TEMP °F	61	61	61	61

TABLE XII
HELIUM DATA TEST TWO
(Room Temperature 66° F.)

Pressure 75 psig

LOAD POUNDS	CLEARANCE IN INCHES RUN 1	RUN 2	RUN 3	AVERAGE
0	.01007	.01001	.01014	.01007
10	.00662	.00669	.00670	.00667
20	.00531	.00540	.00538	.00536
30	.00450	.00454	.00456	.00453
40	.00386	.00395	.00397	.00392
50	.00347	.00358	.00354	.00353
60	.00312	.00322	.00320	.00318
70	.00281	.00292	.00290	.00287
80	.00263	.00272	.00270	.00268
90	.00242	.00251	.00249	.00247
100	.00214	.00222	.00220	.00218
105	.00190	.00195	.00192	.00192
106	-	-	-	-
GAS TEMP °F	68	68	68	68

Pressure 50 psig

LOAD POUNDS	CLEARANCE IN INCHES RUN 1	RUN 2	RUN 3	AVERAGE
0	.01085	.01103	.01089	.01092
10	.00638	.00647	.00630	.00638
20	.00487	.00486	.00487	.00487
30	.00417	.00409	.00409	.00411
40	.00345	.00347	.00346	.00346
50	.00305	.00307	.00303	.00305
60	.00263	.00267	.00265	.00265
65	.00240	.00239	.00231	.00236
66	.00225	.00220	.00217	.00220
67	.00203	.00206	.00178	.00195
68	-	-	-	-
GAS TEMP °F	68	68	68	68

Pressure 25 psig

LOAD POUNDS	CLEARANCE IN INCHES RUN 1	RUN 2	RUN 3	AVERAGE
0	.01246	.01259	.01261	.01255
5	.00720	.00712	.00694	.00708
10	.00551	.00549	.00525	.00541
15	.00460	.00454	.00430	.00448
20	.00402	.00392	.00381	.00391
25	.00354	.00344	.00344	.00347
30	.00281	.00272	.00273	.00275
31	.00253	.00241	.00221	.00238
32	-	-	-	-
GAS TEMP °F	68	68	68	68

TABLE XIII
LOAD - CLEARANCE FOR AIR AT 75 PSIG
OVER A WIDE RANGE OF CLEARANCE

Load (Pounds)	Clearance (Inches)
87	.00124
86	.00136
85	.00145
80	.00153
70	.00166
60	.00179
50	.00194
40	.00219
30	.00261
20	.00313
10	.00407
0	.00641
-2	.00795
-4	.01005
-6	.01449
-6.5	.01667
-6.75	.01833
-7	.02166
-6	.03660
-5	.04630
-4	.06860
-3	.10840
-2	.15337
-1	.21038
-½	.32142

TABLE XIV
AVERAGE OF TEST ONE AND TEST TWO DATA AT 75 PSIG

HELIUM		ARGON		NITROGEN	
LOAD POUNDS	CLEARANCE IN INCHES	LOAD POUNDS	CLEARANCE IN INCHES	LOAD POUNDS	CLEARANCE IN INCHES
0	.01068	0	.00707	0	.00675
10	.00711	10	.00449	10	.00416
20	.00572	20	.00355	20	.00333
30	.00492	30	.00295	30	.00276
40	.00424	40	.00254	40	.00242
50	.00382	50	.00228	50	.00219
60	.00350	60	.00211	60	.00203
70	.00319	70	.00192	70	.00186
80	.00299	80	.00174	80	.00170
90	.00275	85	.00160	85	.00154
100	.00243	87	.00153	87	.00143
102	.00232	89	.00145	88.5	.00134
104	.00218				

AIR		OXYGEN		CARBON DIOXIDE	
LOAD POUNDS	CLEARANCE IN INCHES	LOAD POUNDS	CLEARANCE IN INCHES	LOAD POUNDS	CLEARANCE IN INCHES
0	.00657	0	.00680	0	.00591
10	.00424	10	.00441	10	.00356
20	.00333	20	.00349	20	.00272
30	.00279	30	.00294	30	.00225
40	.00243	40	.00249	40	.00196
50	.00219	50	.00222	50	.00175
60	.00201	60	.00206	60	.00162
70	.00185	70	.00186	70	.00143
80	.00167	80	.00171	80	.00124
85	.00155	85	.00156	80.5	.00120
86	.00150	87	.00145		
87	.00139	89	.00136		

TABLE XV
AVERAGE OF TEST ONE AND TEST TWO DATA AT 50 PSIG

HELIUM		ARGON		NITROGEN	
LOAD POUNDS	CLEARANCE IN INCHES	LOAD POUNDS	CLEARANCE IN INCHES	LOAD POUNDS	CLEARANCE IN INCHES
0	.01144	0	.00730	0	.00731
10	.00682	10	.00408	10	.00399
20	.00526	20	.00315	20	.00315
30	.00449	30	.00263	30	.00263
40	.00391	40	.00228	40	.00228
50	.00350	50	.00198	50	.00198
60	.00308	55	.00182	55	.00180
65	.00272	56	.00174	56	.00169
66	.00243	57	.00156	56.5	.00159
66.5	.00218	58	-	57	-
67	-				

AIR		OXYGEN		CARBON DIOXIDE	
LOAD POUNDS	CLEARANCE IN INCHES	LOAD POUNDS	CLEARANCE IN INCHES	LOAD POUNDS	CLEARANCE IN INCHES
0	.00754	0	.00716	0	.00583
10	.00412	10	.00402	10	.00315
20	.00318	20	.00313	20	.00245
30	.00265	30	.00261	30	.00200
40	.00229	40	.00222	40	.00174
50	.00201	50	.00195	50	.00143
55	.00183	55	.00181	51	.00139
56	.00172	56	.00166	51.5	.00132
56.5	.00160	57	.00156	52	-
57	-	58	-		

TABLE XVI
AVERAGE OF TEST ONE AND TEST TWO DATA AT 25 PSIG

HELIUM

LOAD POUNDS	CLEARANCE IN INCHES
0	.01282
5	.00750
10	.00584
15	.00489
20	.00435
25	.00388
30	.00314
30.5	.00277
31	-

ARGON

LOAD POUNDS	CLEARANCE IN INCHES
0	.00754
5	.00450
10	.00352
15	.00299
20	.00261
25	.00223
26	.00203
26.5	.00191
27	-

NITROGEN

LOAD POUNDS	CLEARANCE IN INCHES
0	.00833
5	.00453
10	.00354
15	.00299
20	.00265
25	.00225
26	.00209
27	-

AIR

LOAD POUNDS	CLEARANCE IN INCHES
0	.00804
5	.00464
10	.00360
15	.00305
20	.00270
25	.00225
26	.00206
26.5	.00189
27	-

OXYGEN

LOAD POUNDS	CLEARANCE IN INCHES
0	.00673
5	.00450
10	.00348
15	.00296
20	.00255
25	.00218
26	.00196
26.5	.00184
27	-

CARBON DIOXIDE

LOAD POUNDS	CLEARANCE IN INCHES
0	.00575
5	.00363
10	.00272
15	.00226
20	.00205
25	.00160
26	-

TABLE XVII
ARGON DATA TEST THREE
(Room Temperature 80° F)

Pressure 75 psig

LOAD	CLEARANCE IN INCHES			
POUNDS	RUN 1	RUN 2	RUN 3	AVERAGE
0	.00701	.00710	.00670	.00694
10	.00390	.00400	.00387	.00392
20	.00279	.00293	.00285	.00286
30	.00220	.00237	.00221	.00226
40	.00190	.00202	.00190	.00194
50	.00164	.00180	.00165	.00170
60	.00142	.00156	.00143	.00147
70	.00127	.00140	.00130	.00132
80	.00106	.00119	.00109	.00111
85	.00096	.00099	.00096	.00097
86	.00092	.00093	.00092	.00092
87	.00087	.00090	.00088	.00088
88	-	-	-	-
GAS TEMP °F	89	88	89	89

TABLE XVIII
CARBON DIOXIDE DATA TEST THREE
(Room Temperature 80° F)

Pressure 75 psig

LOAD POUNDS	CLEARANCE IN INCHES RUN 1	RUN 2	RUN 3	AVERAGE
0	.00576	.00566	.00559	.00564
10	.00305	.00292	.00295	.00297
20	.00204	.00207	.00207	.00206
30	.00163	.00165	.00166	.00165
40	.00135	.00139	.00139	.00138
50	.00114	.00120	.00120	.00118
60	.00095	.00104	.00105	.00103
70	.00080	.00089	.00090	.00086
80	.00055	.00068	.00070	.00064
81	.00053	.00058	.00059	.00057
GAS TEMP °F	88	88	89	88

TABLE XIX
OXYGEN DATA TEST THREE
(Room Temperature 80° F.)

Pressure 75 psig

LOAD	CLEARANCE IN INCHES			
POUNDS	RUN 1	RUN 2	RUN 3	AVERAGE
0	.00659	.00658	.00651	.00656
10	.00390	.00380	.00388	.00386
20	.00284	.00282	.00278	.00281
30	.00220	.00221	.00219	.00220
40	.00186	.00184	.00183	.00184
50	.00159	.00159	.00159	.00159
60	.00136	.00136	.00135	.00136
70	.00120	.00120	.00120	.00120
80	.00100	.00100	.00099	.00100
85	.00085	.00089	.00086	.00087
86	.00081	.00079	.00080	.00080
87	-	-	-	-
GAS TEMP °F	87	87	87	87

TABLE XX
OXYGEN DATA AT DIFFERENT TEMPERATURES

Oxygen 76° F at 75 psig
(Room Temperature 78° F.)

LOAD POUNDS	CLEARANCE IN INCHES RUN 1	RUN 2	RUN 3	AVERAGE
0	.00637	.00617	.00637	.00630
10	.00364	.00365	.00367	.00365
20	.00367	.00260	.00265	.00264
30	.00213	.00207	.00207	.00209
40	.00173	.00175	.00174	.00174
50	.00147	.00147	.00149	.00148
60	.00127	.00127	.00129	.00128
70	.00112	.00115	.00113	.00113
80	.00095	.00100	.00097	.00097
85	.00086	.00089	.00089	.00080
86	.00082	.00086	.00082	.00083
87	.00077	.00079	.00079	.00081
88	-	-	-	-
GAS TEMP °F	76	76	76	76

Oxygen 92° F at 75 psig
(Room Temperature 95° F.)

LOAD POUNDS	CLEARANCE IN INCHES RUN 1	RUN 2	RUN 3	AVERAGE
0	.00622	.00620	.00615	.00619
10	.00360	.00370	.00375	.00368
20	.00257	.00259	.00270	.00262
30	.00210	.00209	.00210	.00210
40	.00172	.00170	.00170	.00171
50	.00148	.00135	.00148	.00144
60	.00128	.00126	.00126	.00127
70	.00111	.00110	.00110	.00110
80	.00090	.00085	.00090	.00088
85	.00082	.00075	.00082	.00080
86	.00078	.00072	.00078	.00076
87	.00070	.00070	.00072	.00071
88	-	-	-	-
GAS TEMP °F	92	93	92	92

Oxygen 87° F at 75 psig
(Room Temperature 88° F.)

LOAD POUNDS	CLEARANCE IN INCHES RUN 1	RUN 2	RUN 3	AVERAGE
0	.00642	.00635	.00631	.00636
10	.00370	.00372	.00363	.00368
20	.00267	.00273	.00271	.00270
30	.00212	.00213	.00213	.00213
40	.00178	.00175	.00174	.00176
50	.00149	.00150	.00144	.00148
60	.00128	.00129	.00125	.00127
70	.00113	.00111	.00110	.00111
80	.00093	.00093	.00092	.00093
85	.00081	.00071	.00082	.00078
GAS TEMP °F	87	87	87	87

C. Discussion of Results

From the beginning of the work reported in this thesis it was hoped that a comparison could be made concerning the load carrying capacities of monatomic, diatomic, and triatomic gases. The experimental work pursued has resulted in data which does predict the load carrying capacities of these several working fluids in a comparative way.

The data included in this report were taken on the experimental apparatus both before and after its modification. In no way did any of these mechanical modifications and improvements alter the comparative results obtained. These modifications did, however, improve the accuracy and repeatability of the data which could be collected from the various tests.

As has been previously mentioned, the factors which seem to have had the greatest effect on the data are mechanical in nature. When the size of the clearances being measured are given careful consideration, it can be understood that the apparatus must be rigid and maintain its dimensions to a high degree of accuracy if data taken at different times can be expected to repeat themselves. A ten degree change in room temperature caused enough distortion of the structure to deflect the dial indicator four thousandths of an inch which is approximately four hundred times greater than the accuracy to which data were taken.

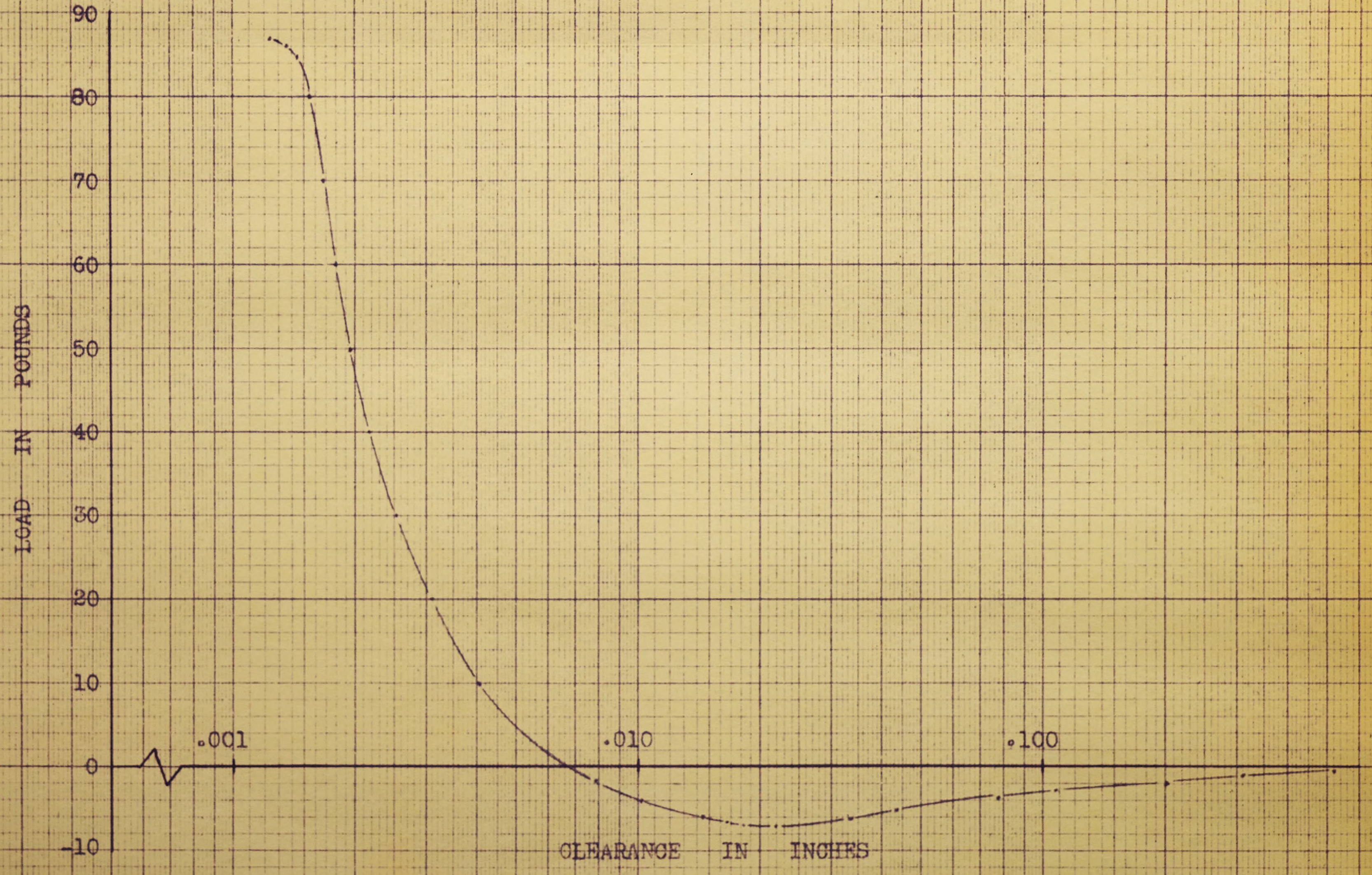
In spite of both the mechanical imperfections involved in any experimental apparatus and the inability to maintain a fixed environment in which to conduct the investigation, the test results in every case gave the same comparative results. These results were:

1. The load versus clearance curves (Graphs 2 thru 7) always placed the various gases in the same relative position in each of the tests conducted.
2. The slope of the load versus clearance curves were comparable within the accuracy attainable with our test apparatus. This slope was essentially unaffected by any of the mechanical modifications to the apparatus.

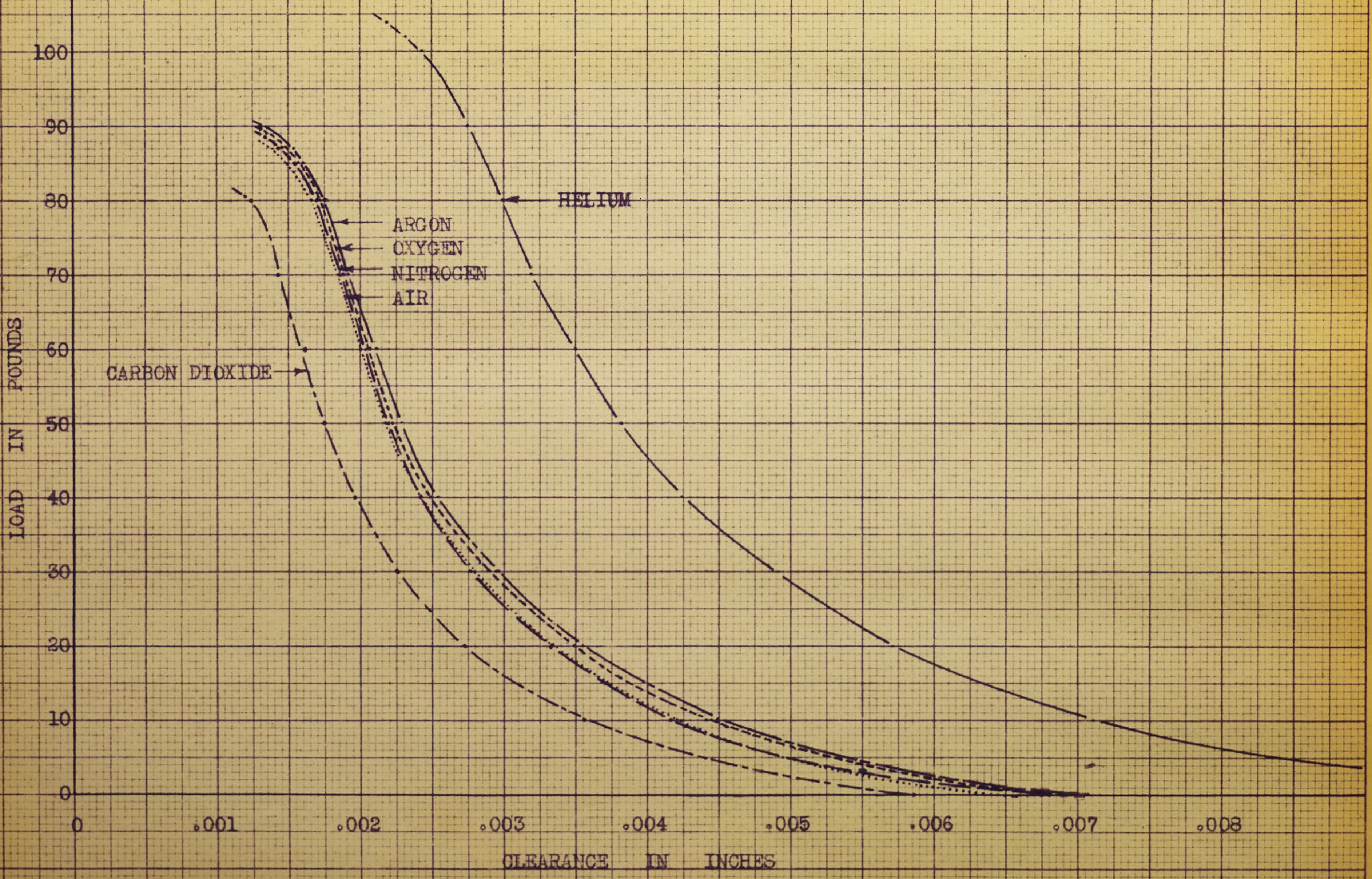
It can be seen from the data shown in Tables I thru XII that the agreement between any two runs of data for the same test are very close, particularly if the change in clearance between two loads is compared between runs. If the curves in Test One are compared with the curves of Test Two at seventy-five psig shown in Graph 5, it will be noted that they are of almost identical shape but the curves of Test Two are shifted to the left in the direction of less clearance by practically the same amount for each gas at each load.

In comparing the curves for the average of Test One and Two at seventy-five, fifty, and twenty-five psig (Graphs 2, 3, and 4) it can be seen that the curves for each gas are similar in shape, nearly parallel, and that the relative location of each gas is the same at each of the three pressures tested. The data obtained in Test Three are shown in Graph 6. A comparison of the data obtained in Test Three with the average of Test One and Two reveal a slight change in the shape of the curves but the relative location of the curves and the magnitude of the maximum load remained unchanged, (Graph 7). Graph 8 shows a comparison between data for oxygen taken at two different temperatures on two different days. It indicates that temperature change has little effect on the shape and location of the curves. It also indicates that with the modified test apparatus used in Test Three, consistent reproduction of the data could be obtained.

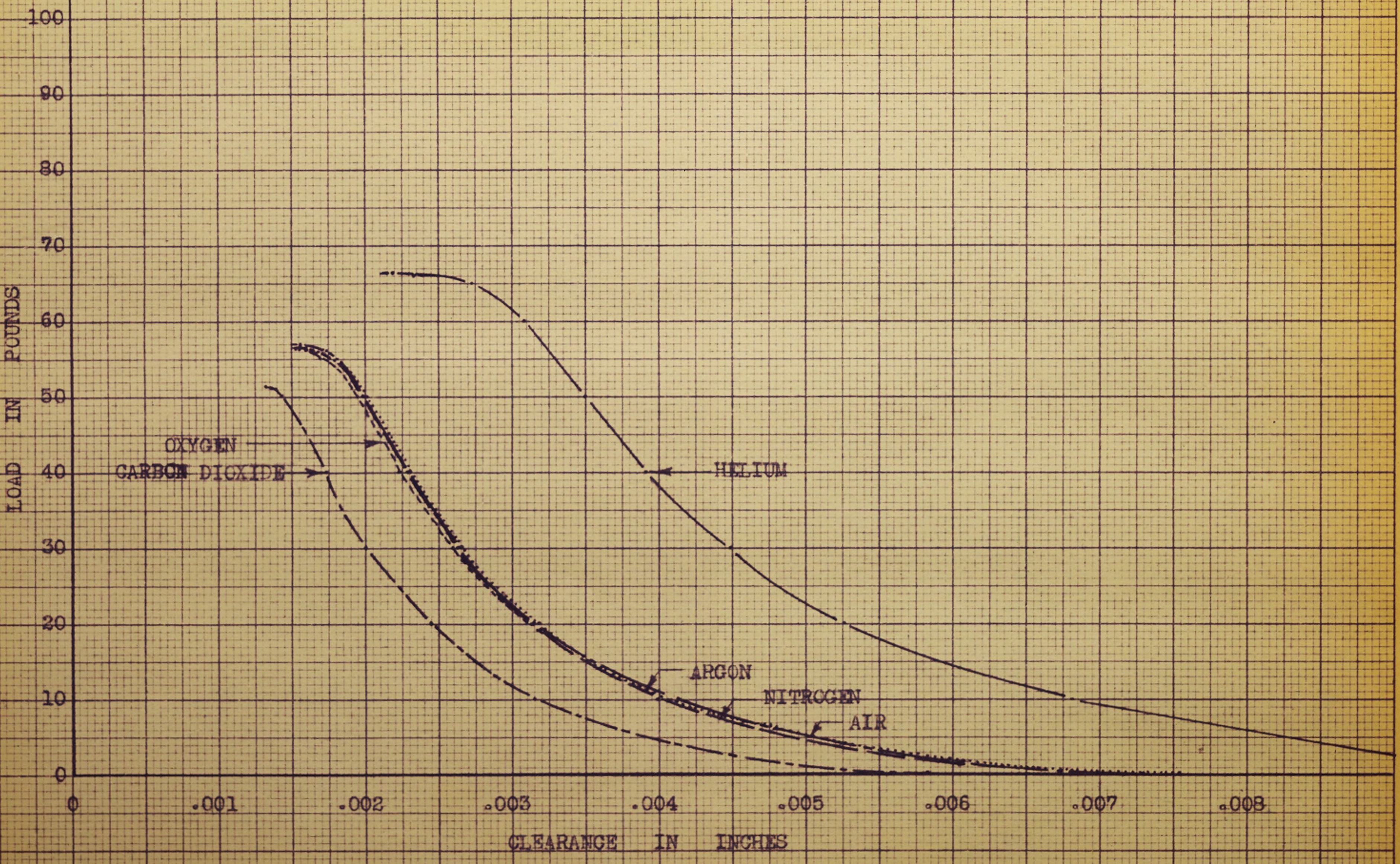
Graph 1 shows the load carrying capacity of the thrust bearing over a wide range of clearance for air at seventy-five psig. It can be seen that a partial vacuum is created under a portion of the bearing for negative loads. The vacuum is increased further as the gap is forcibly increased by loads which tend to pull the plates apart. Seven pounds was the maximum negative load carried by the bearing.



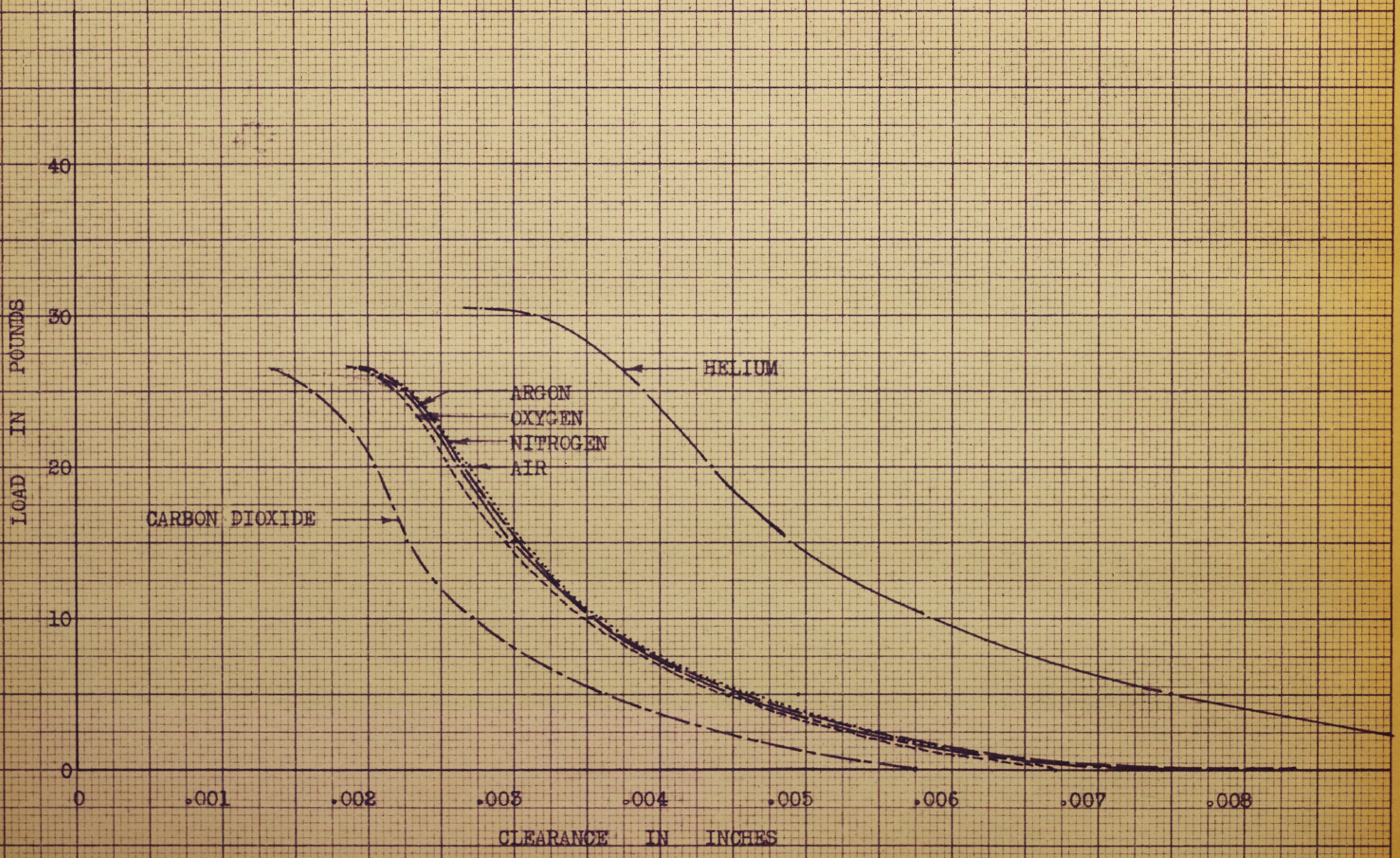
GRAPH 1 LOAD - CLEARANCE FOR AIR AT 75 PSIG OVER A WIDE RANGE OF CLEARANCE



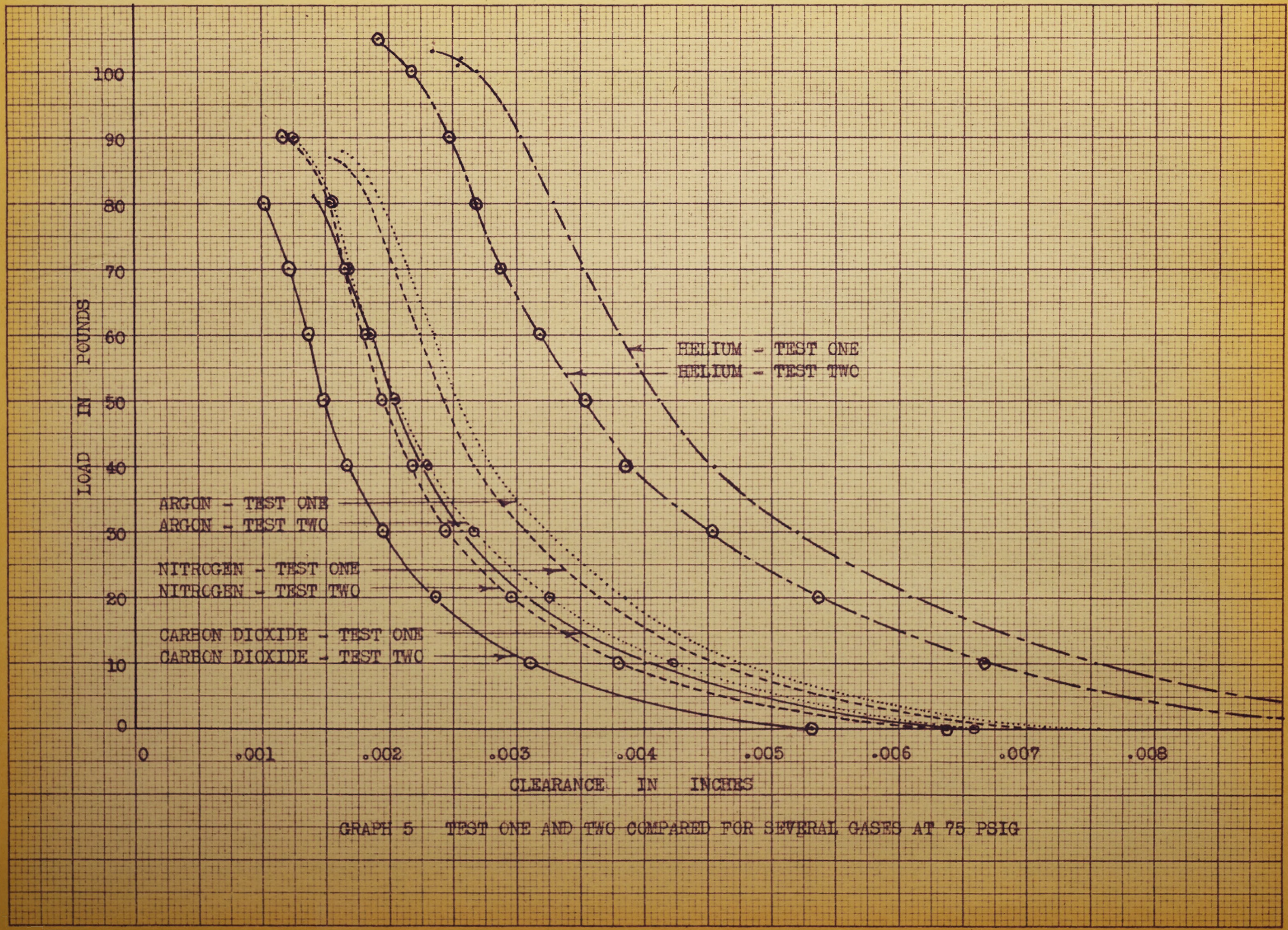
GRAPH 2 - LOAD - CLEARANCE FOR VARIOUS GASES AT 75 PSIG



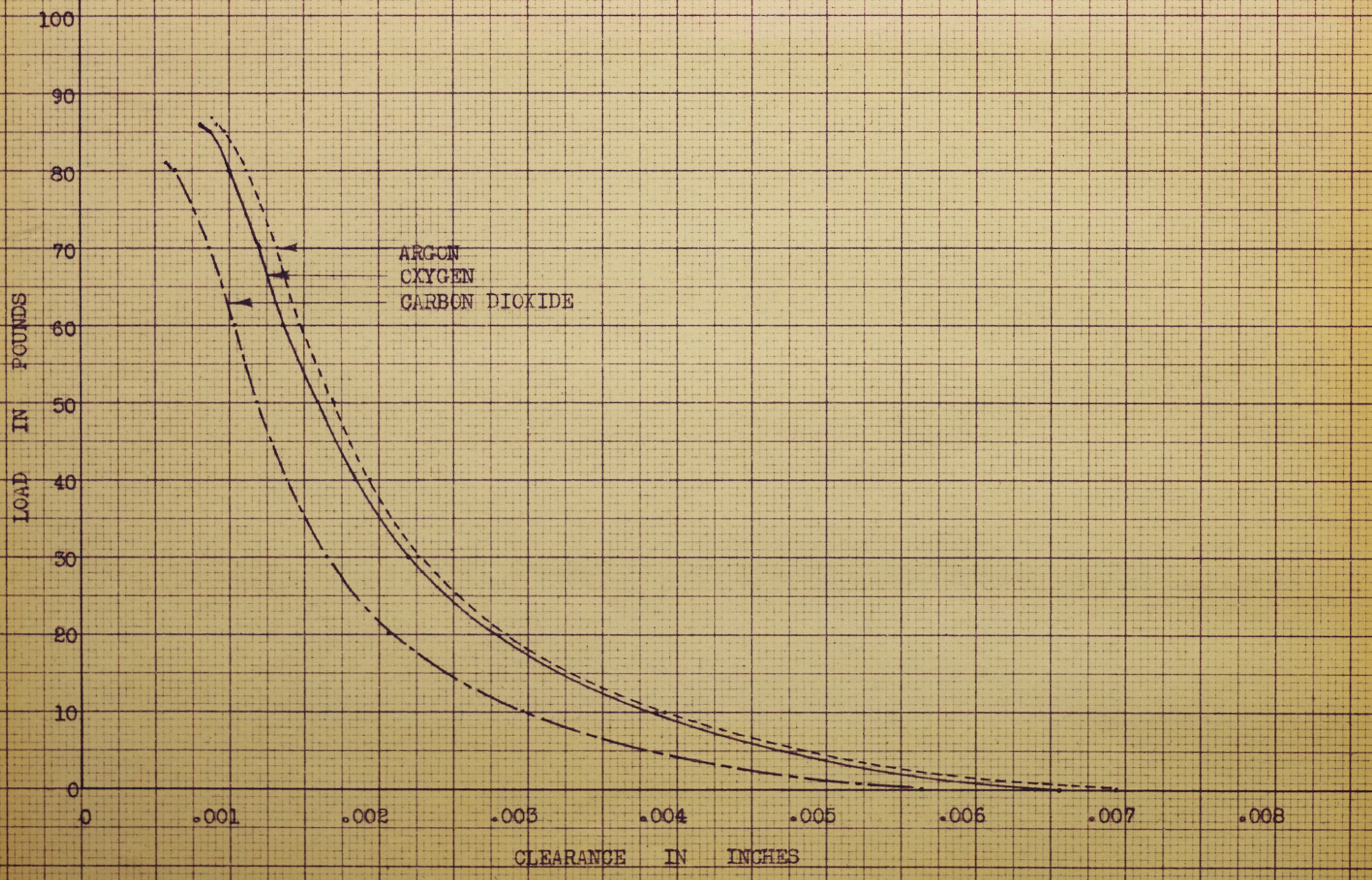
GRAPH 3 LOAD - CLEARANCE FOR VARIOUS GASES AT 50 PSIG



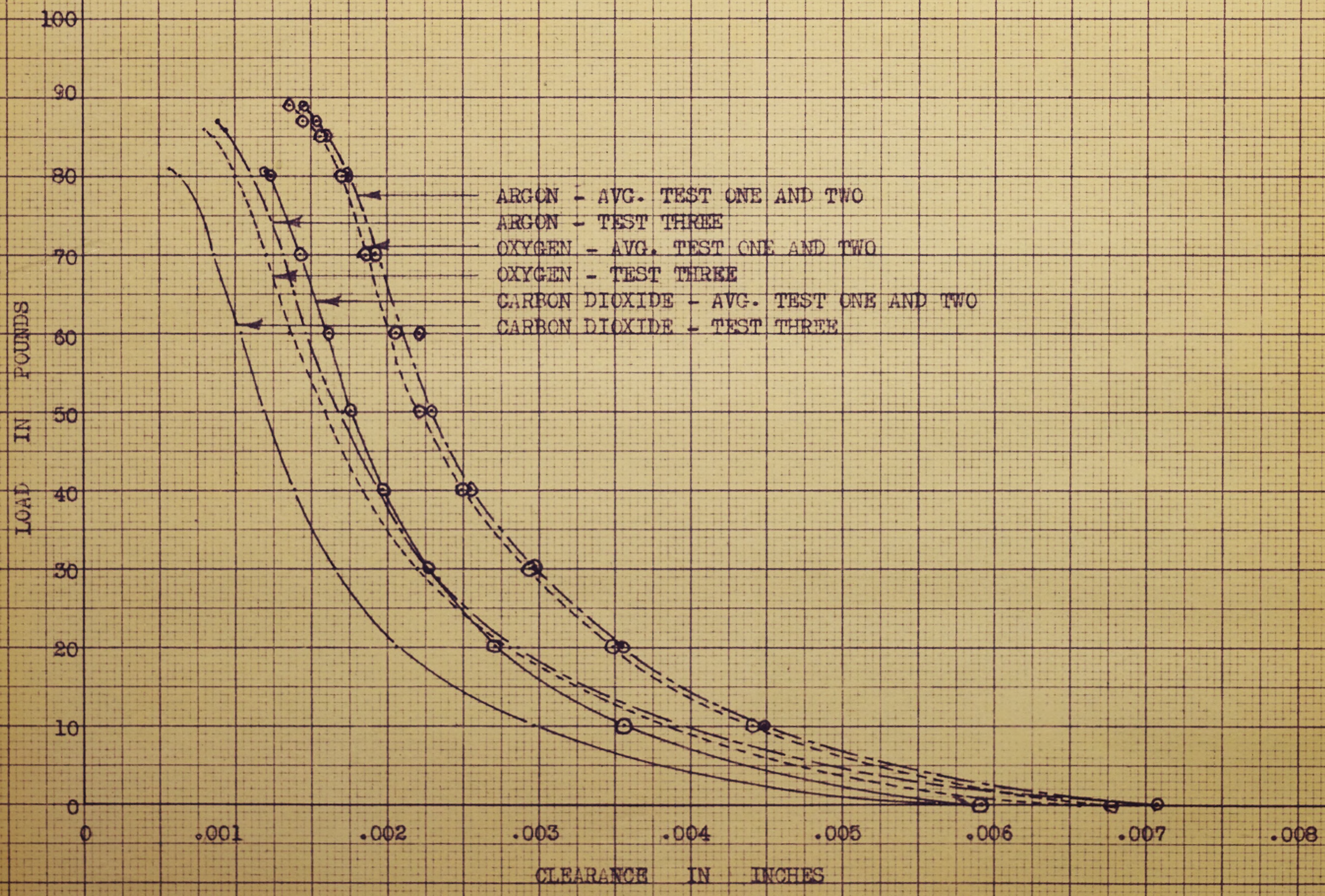
GRAPH 4 LOAD - CLEARANCE FOR VARIOUS GASES AT 25 PSIG



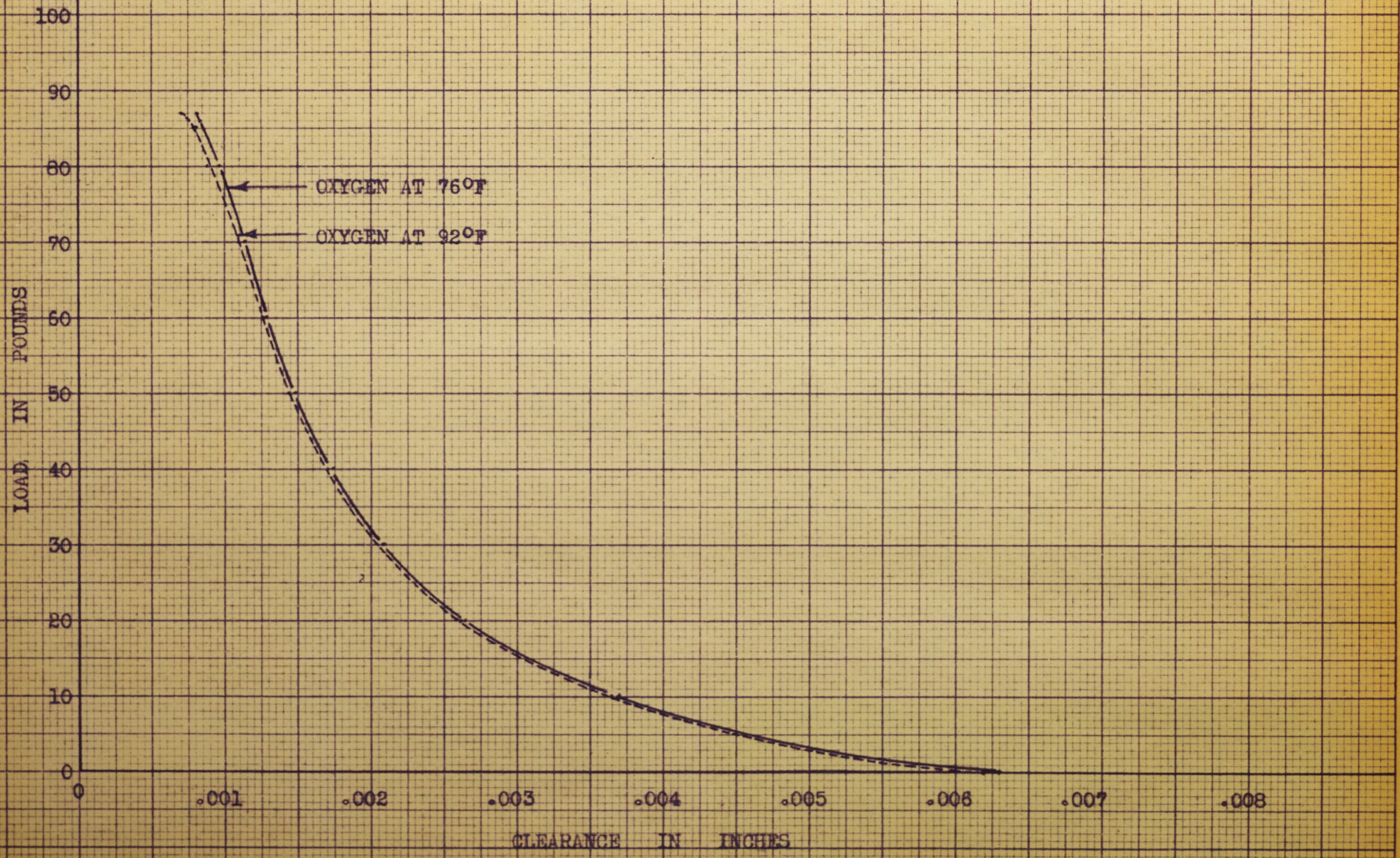
GRAPH 5 TEST ONE AND TWO COMPARED FOR SEVERAL GASES AT 75 PSIG



GRAPH 6 LOAD - CLEARANCE FOR VARIOUS GASES, TEST THREE



GRAPH 7 TEST THREE COMPARED WITH THE AVERAGE OF TEST ONE AND TWO FOR VARIOUS GASES AT 75 PSIG



GRAPH 8 LOAD - CLEARANCE FOR OXYGEN AT TWO TEMPERATURES

IV. CONCLUSIONS

All data obtained from the experiment confirm the validity of the relative load carrying capacity of the various gases tested as shown in Plates II thru VII. From these graphs it can be seen that the monatomic gases helium and argon exhibit a greater clearance for a given load and greater total load carrying capacity than the diatomic gases oxygen and nitrogen which in turn have a greater clearance for a given load and a greater total load carrying capacity than the triatomic gas carbon dioxide. This is further substantiated when we compare argon, a monatomic gas of molecular weight forty and carbon dioxide, a triatomic gas of molecular weight forty-four. These two gases are of approximately the same molecular weight but the monatomic gas has a greater clearance and load carrying capacity.

Molecular weight also appears to affect load carrying capacity as seen in comparing the two monatomic gases helium, molecular weight four and argon, molecular weight forty. It appears that an increase in molecular weight decreases clearance for a given load and decreases total load carrying capacity.

The effect of temperature change for oxygen at seventy-five psig is shown in Graph 8. From the curves it appears that temperature has little effect on the load carrying capacity of a bearing for the temperature range observed.

In comparing once again the curves in Graphs 2, 3, and 4, it is noted that the break off point for maximum load lies along an approximate straight line. It is felt by the author that the sudden collapsing of the bearing at small clearances is due to the restriction of flow through the bearing caused by the boundary layer on the top and bottom thrust bearing plate. The boundary layer thickness on a flat plate is usually expressed as a function of the kinematic viscosity in the form

$$\delta = \frac{(4.64)(X)}{\sqrt{\frac{U_s X}{\nu}}} \qquad (10)$$

where δ = the boundary layer thickness on a flat plate with laminar flow

U_s = velocity of gas across the plate

X = distance from the leading edge

ν = kinematic viscosity

This equation indicates that gases with high kinematic viscosities would have thicker boundary layers under the same conditions than those with lower kinematic viscosities. Therefore, gases with high kinematic viscosities would collapse at less clearance due to the flow restriction of the thicker boundary layer. The kinematic viscosities of the gases tested at 80° F are as follows (11):

Helium	136.4×10^{-5} ft^{-2}/sec
Argon	14.9×10^{-5} ft^{-2}/sec
Oxygen	17.07×10^{-5} ft^{-2}/sec
Nitrogen	16.82×10^{-5} ft^{-2}/sec
Air	16.88×10^{-5} ft^{-2}/sec
Carbon Dioxide	8.96×10^{-5} ft^{-2}/sec

It can be seen from the curves shown in Graphs 2, 3, and 4 that the break-off point for the gases are as predicted. Thus, the load carrying capacities of the various working fluids have been shown to lie in the relative locations expected based on their properties of ratio of specific heat, molecular weight, and kinematic viscosity. The validity of the experimental apparatus and test set up have been attested to. There are many additional areas in which more work would be useful to the designer of bearings of this type. Some of these areas which would be worthy of investigation are:

1. Testing bearings of different sizes, hole arrangements, and configurations to determine the effect on load carrying capacity.
2. A study of the operating characteristic of a bearing at small clearances to determine stability and boundary layer effects with load.
3. An investigation of the pressure profile between two flat plates loaded and supplied with air in a similar manner to the bearing tested.
4. The effect of high temperature on the operating characteristics of a hydrostatic thrust bearing.
5. The effect of rotational speed on the load carrying capacity of a hydrostatic bearing.

BIBLIOGRAPHY

1. HIRN, G., 1854, "Sur les Principaux Phenomenes qui Presentent les Frottements Mediats", Bull. sec. ind. Mulhouse, Vol. 26, p. 188.

2. SHIWALKER, B. D., 1960, "The Status of Gas-Lubricated Bearings", Missouri School of Mines and Metallurgy Thesis number T 1280, c. 2, p. 9 and p. 109.

3. OBERT, E. F., 1960, "Concepts of Thermodynamics", p. 54 and p. 55.

4. LAUB, J. H., "Hydrostatic Gas Bearings", ASME Paper No. 59, Lub-1.

5. RICHARDSON, H. H. and GRINNELL, S. K., 1957, "Design Study of a Hydrostatic Gas Bearing with Inherent Orifice Compensation", Trans. ASME, Vol. 79, No. 1, pp. 11-21.

6. WUNSCH, H. L., 1958, "Design Data on Flat Air Bearings When Operating Under Steady Conditions of Load", Machinery, Vol. 93, No. 2394, pp. 765-775.

7. PIGOTT, J. D., and MACKS, E. F., 1954, "Air Bearing Studies at Normal and Elevated Temperatures", Lubrication Engineering, Vol. 10, No. 1, pp. 29-33.

8. COREY, T. L., TYLER, C. M., ROWLAND, H. H., and KIPP, E. M., 1956, "Behavior of Air in the Hydrostztic Lubrication of Loaded Spherical Bearings", Trans. ASME, Vol. 78, pp. 893-898.

9. McNEILLY, V. H., "Design and Use of Pheumostatic Bearings", ASLE Paper No. 60, AM-5A-2.

10. ECKERT, E. R. G., and DRAKE, R. M., 1959, "Heat and Mass Transfer", p. 140.

11. IBID, Reference 10, pp. 504-506.

VITA

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He attended Southern Illinois University from September 1948 to June 1950 and Washington University from September 1950 to June 1953 where he received a Bachelor of Science Degree in Industrial Engineering in June 1953.

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He was married in June, 1953, and has one son and two daughters, born in December 1955, January 1958, and January 1961.